



**Effects of Ship Compartment
Hydrocarbon Fuel Fire
and
Water Mist Fire Extinguishing
on
RF Propagation
in
the 2.4 GHz ISM Band**

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LT Christos Deyannis
LT Dimitrios Xifaras**

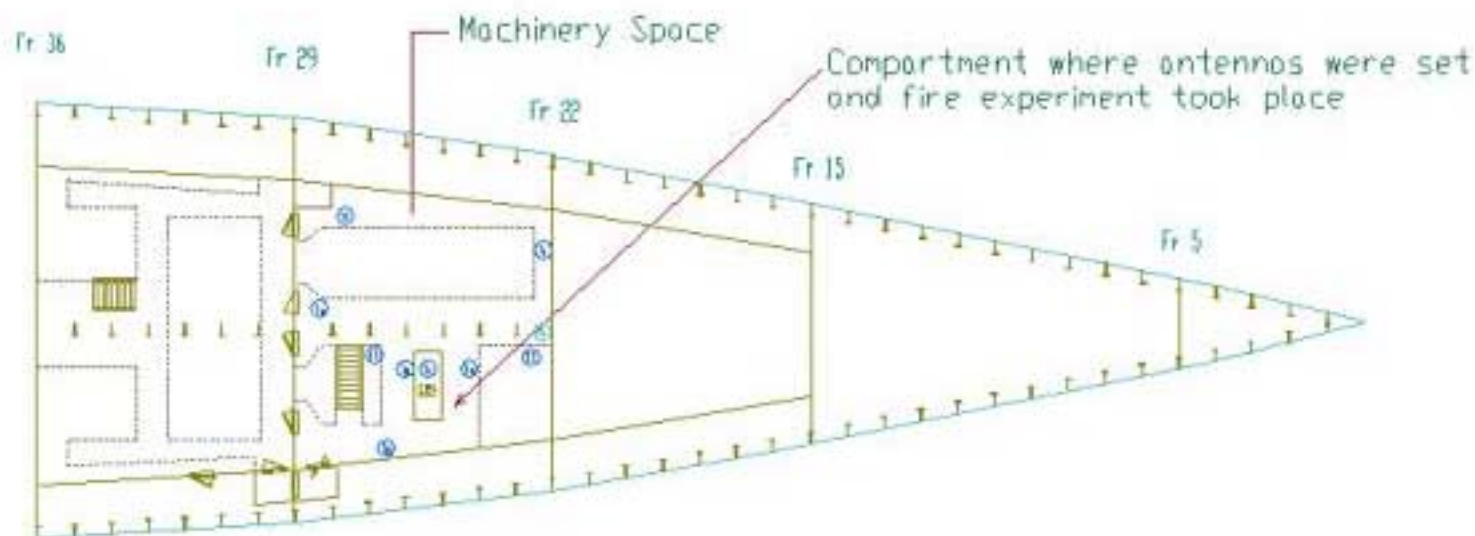
Naval Postgraduate School, Monterey, CA, July 1999

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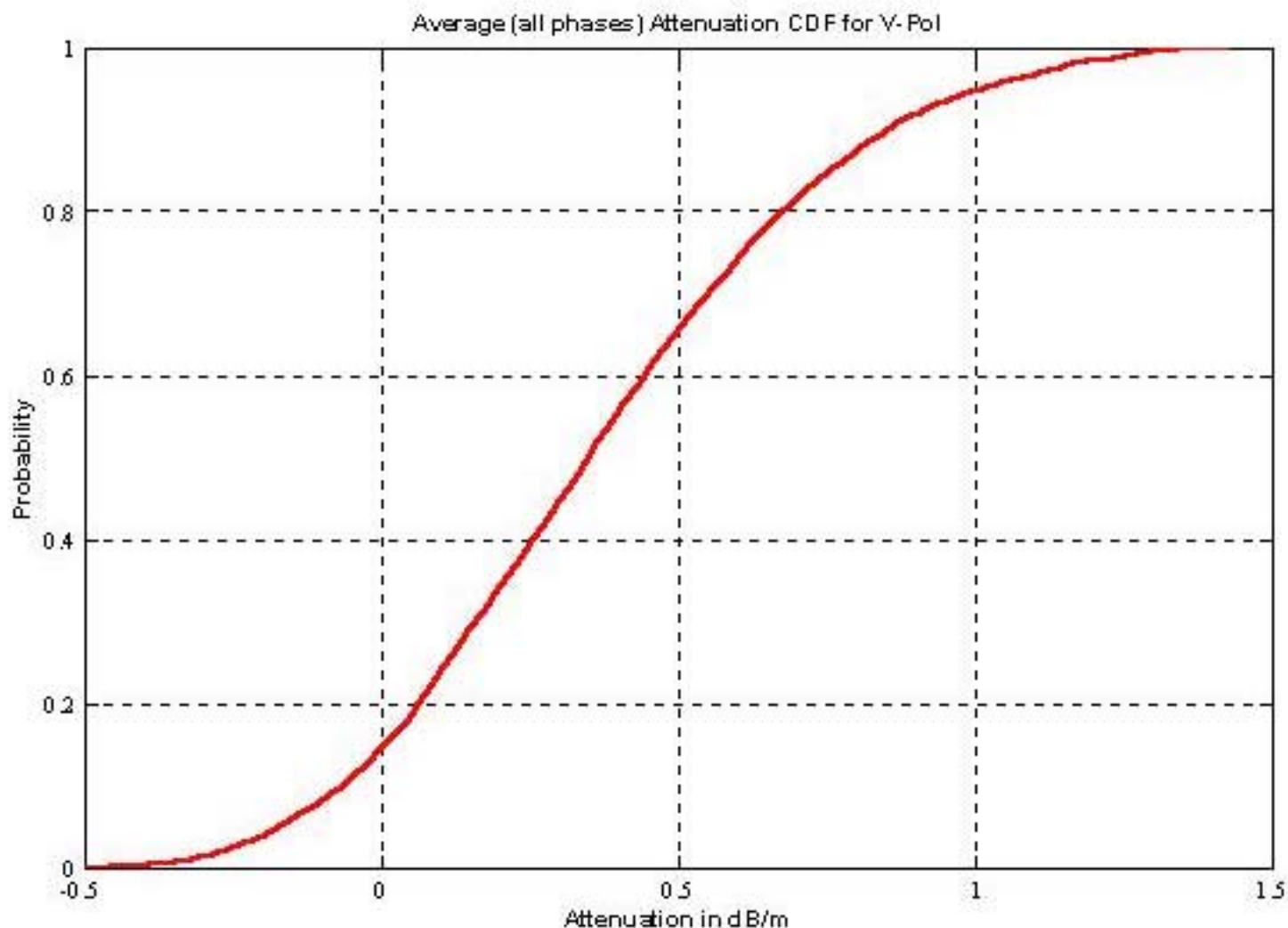
Ex-USS Shadwell Instrumented Section



General view of hold level instrumentation locations
(Lower level)

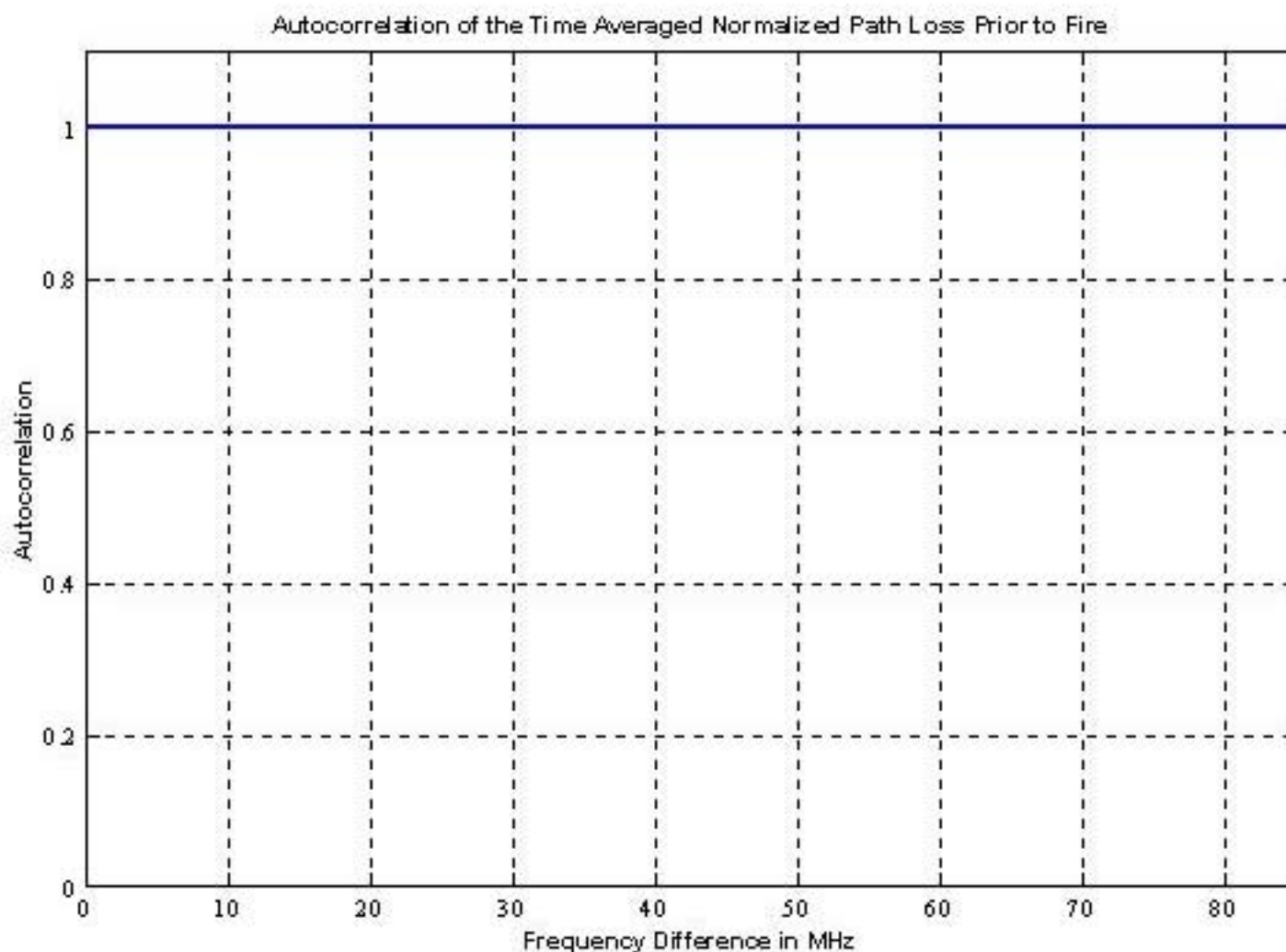


Average Attenuation Cumulative Distribution Function for Directional Antennas, V-Pol



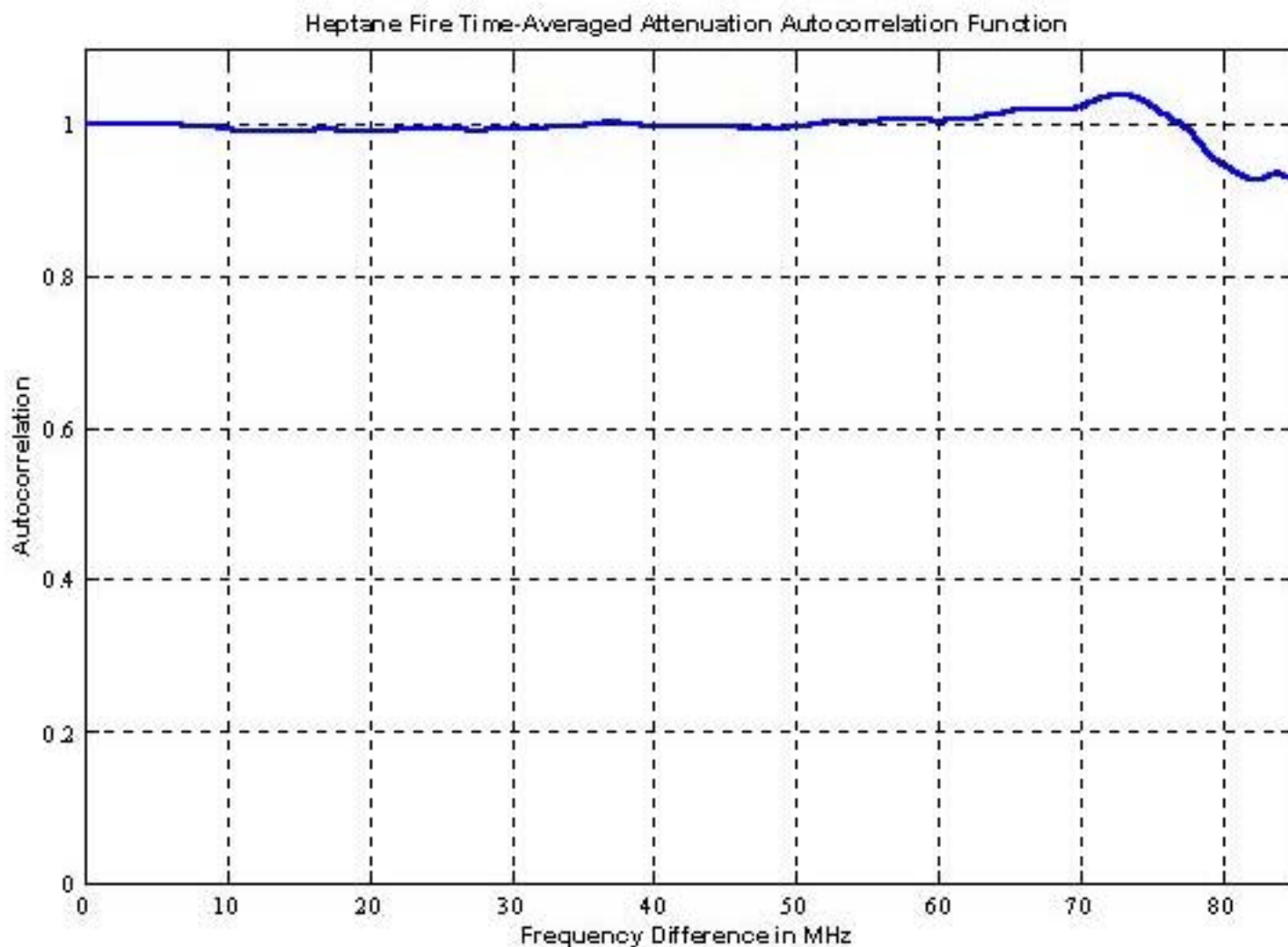


Normalized Autocorrelation Function for Directional Antennas Prior to Fire, V-Pol



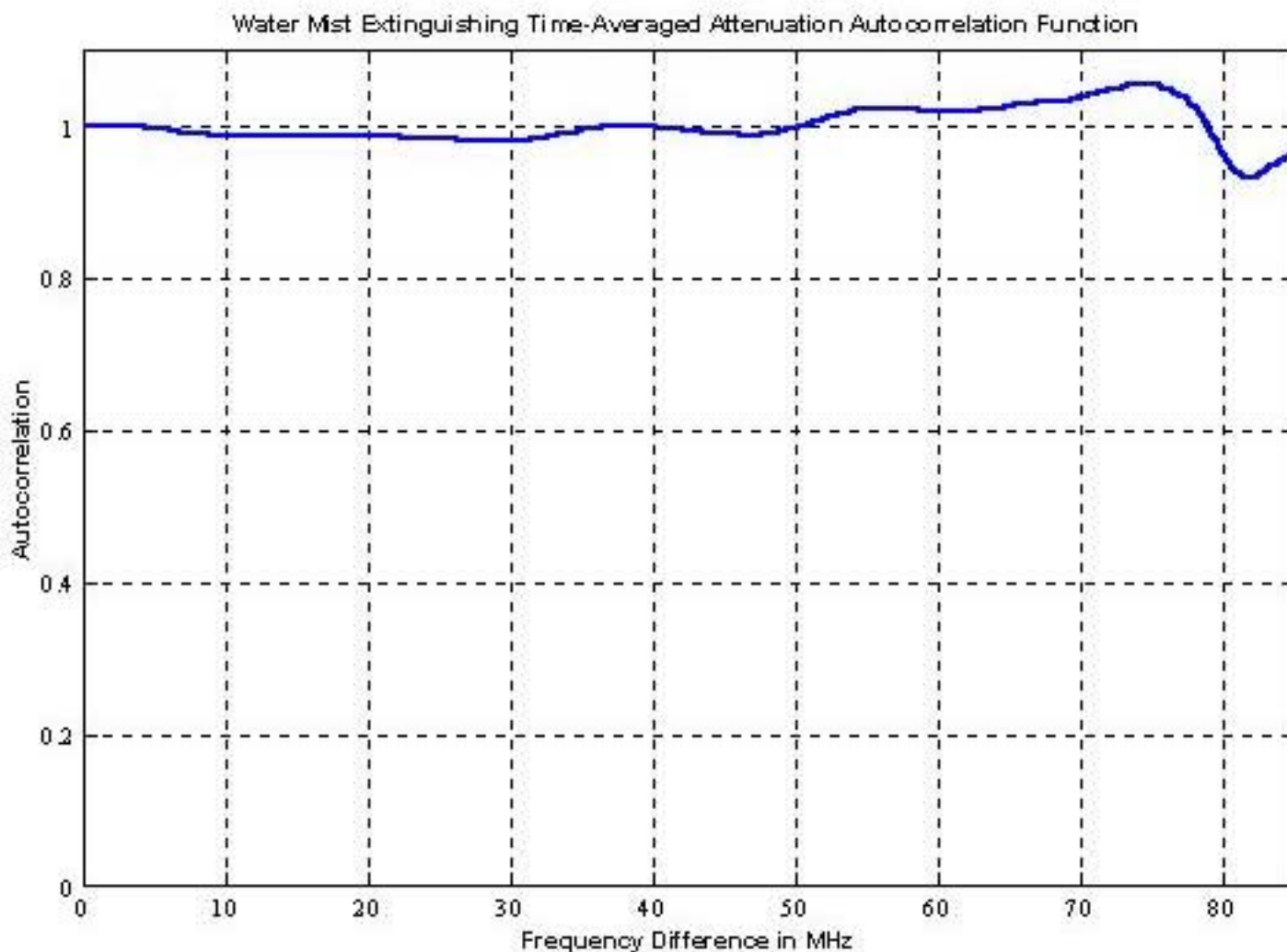


Heptane Fire Normalized Autocorrelation Function for Directional Antennas, V-Pol



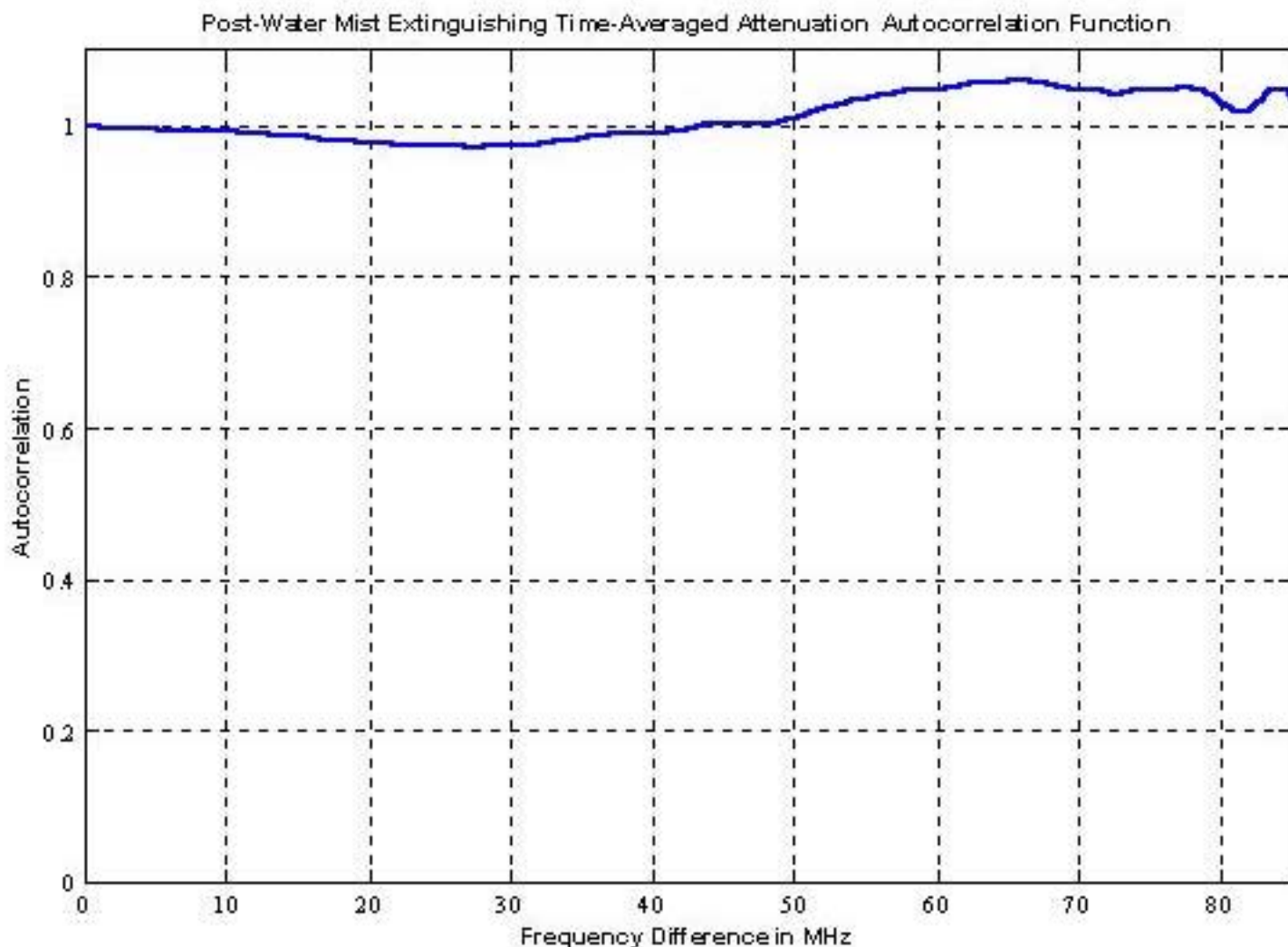


Water Mist Extinguishing Normalized Autocorrelation Function for Directional Antennas, V-Pol



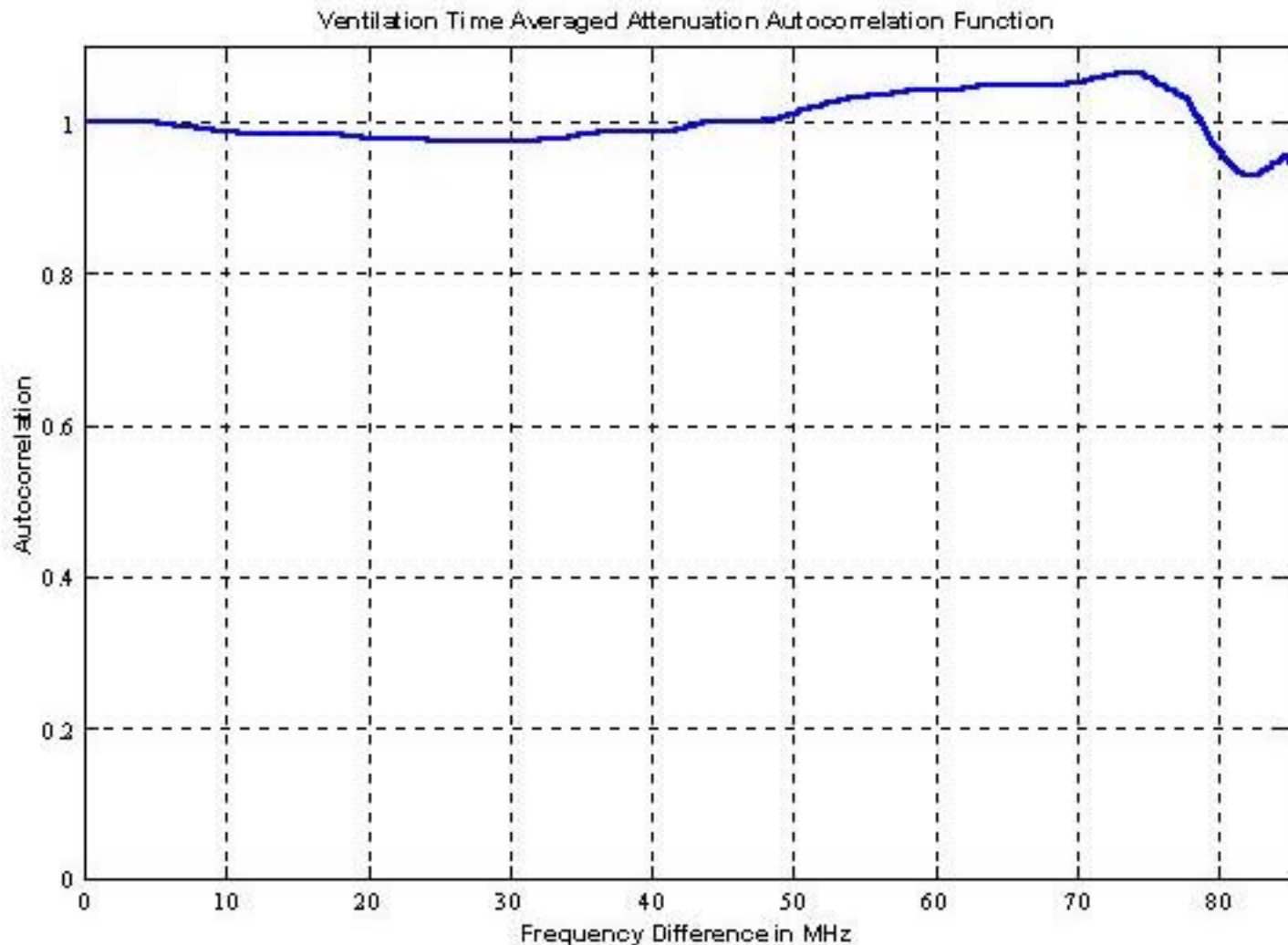


Post-Water Mist Extinguishing Normalized Autocorrelation Function for Directional Antennas, V-Pol





Ventilation Phase Normalized Autocorrelation Function for Directional Antennas, V-Pol

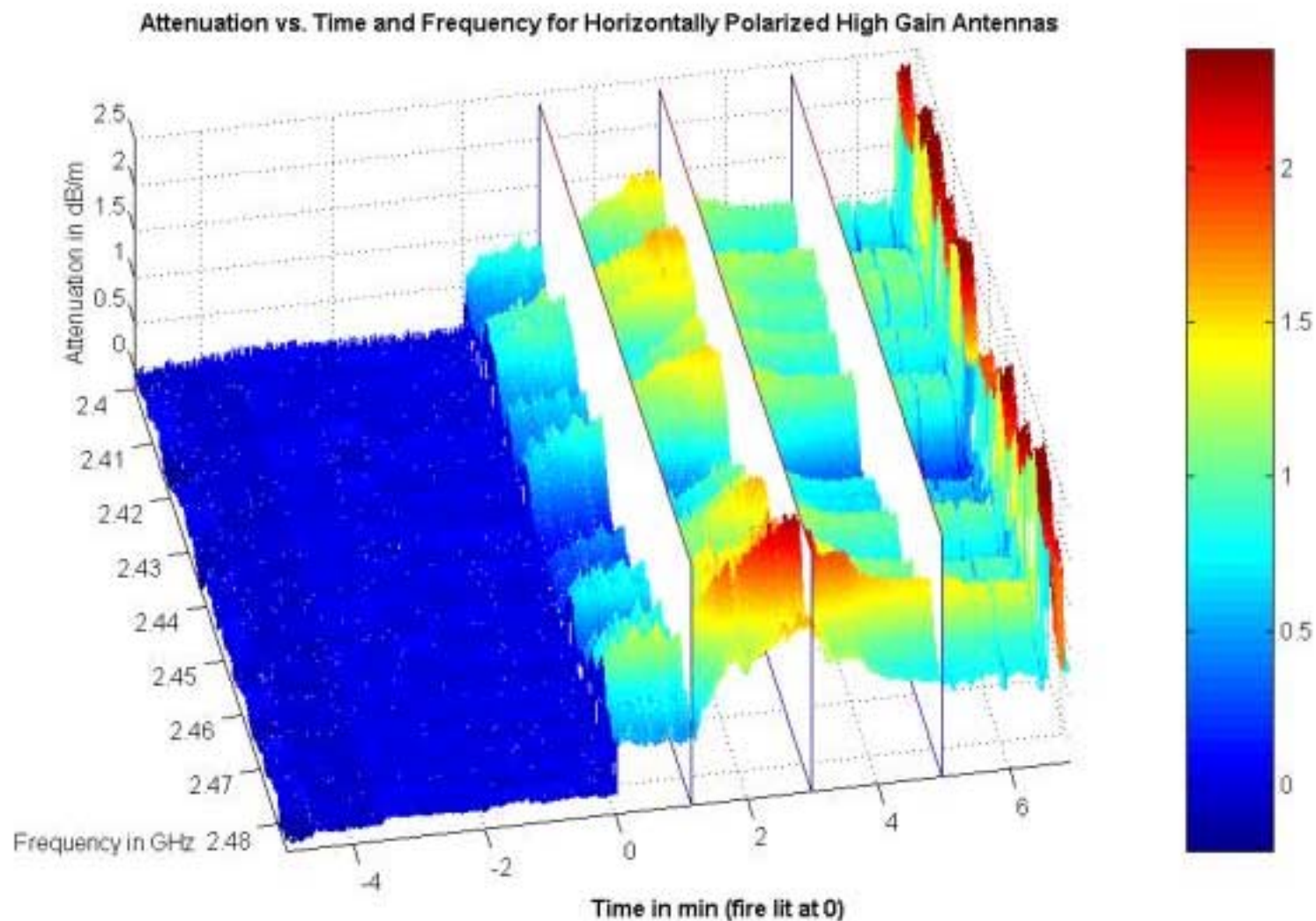




Heptane Fire Results for Horizontally Polarized Directional (High Gain) Antennas



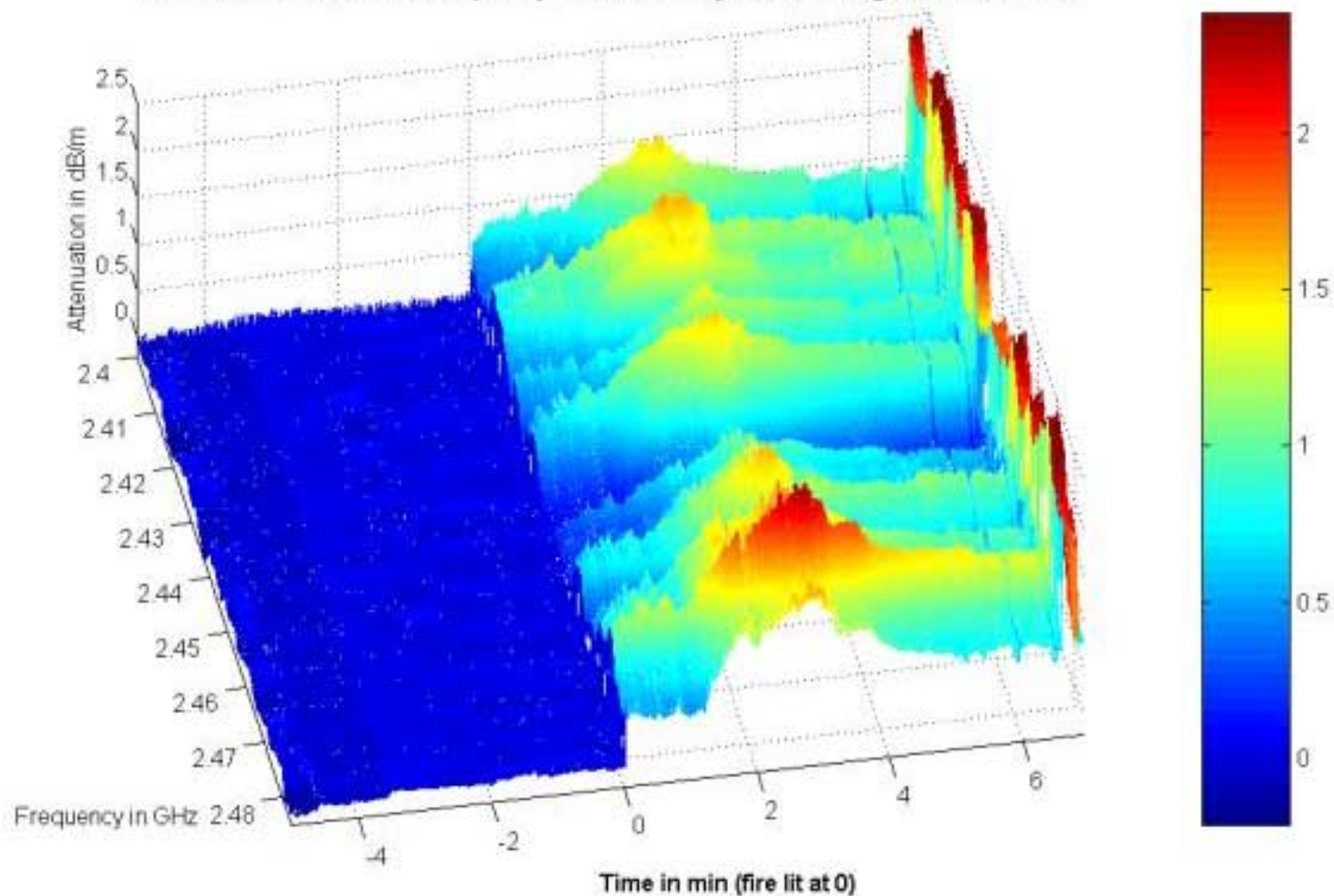
Attenuation for Directional Antennas, H-Pol





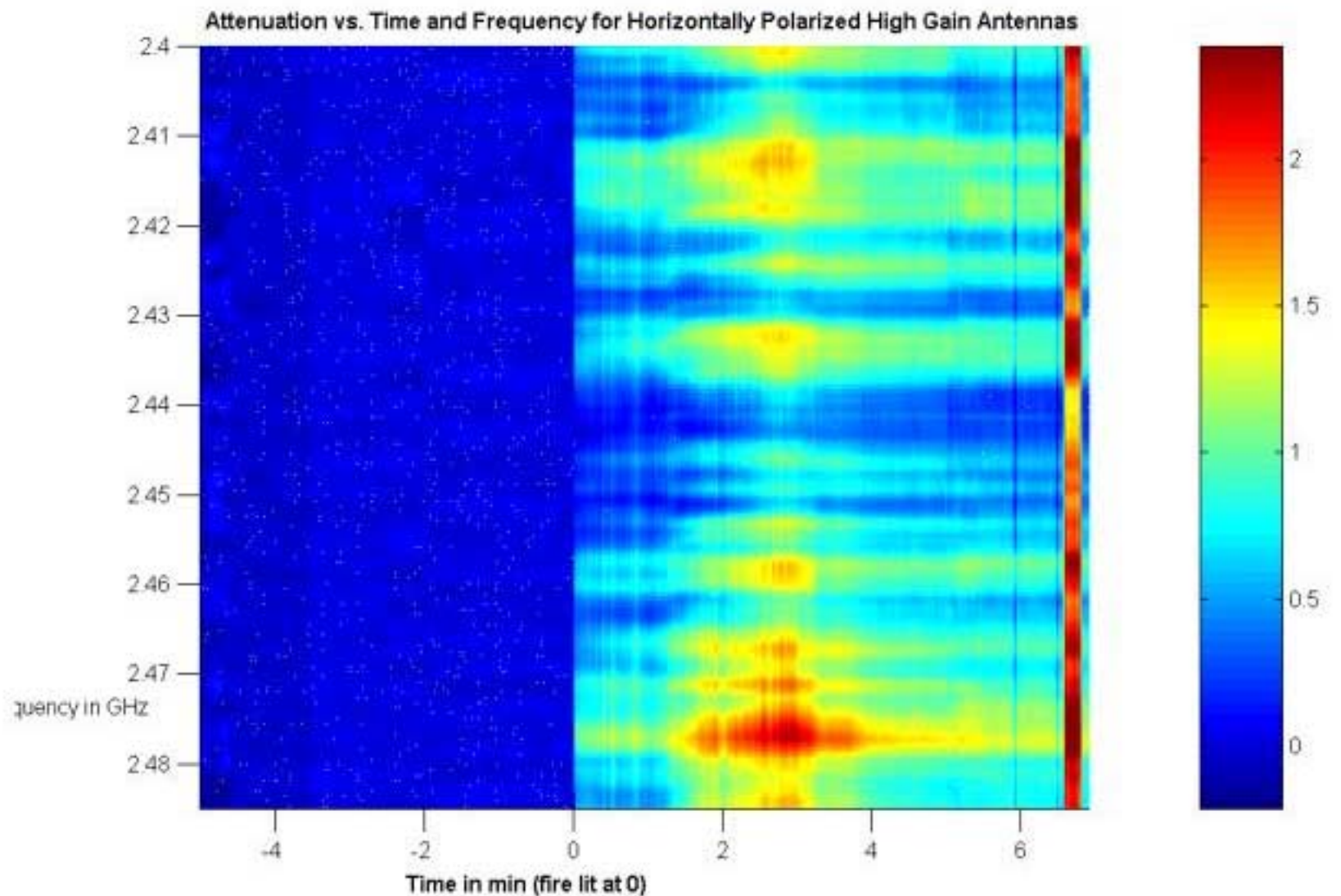
Attenuation for Directional Antennas, H-Pol

Attenuation vs. Time and Frequency for Horizontally Polarized High Gain Antennas



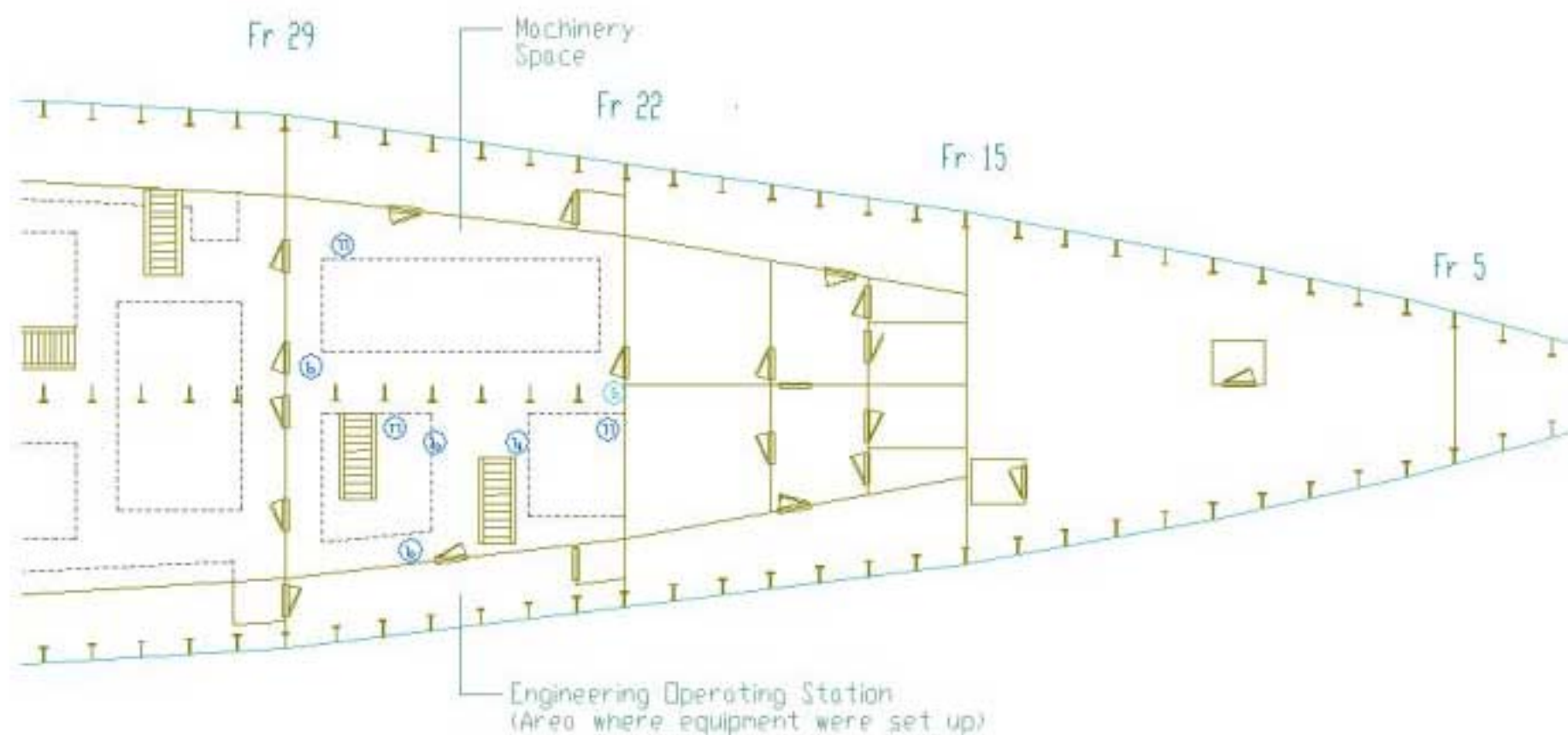


Attenuation for Directional Antennas, H-Pol





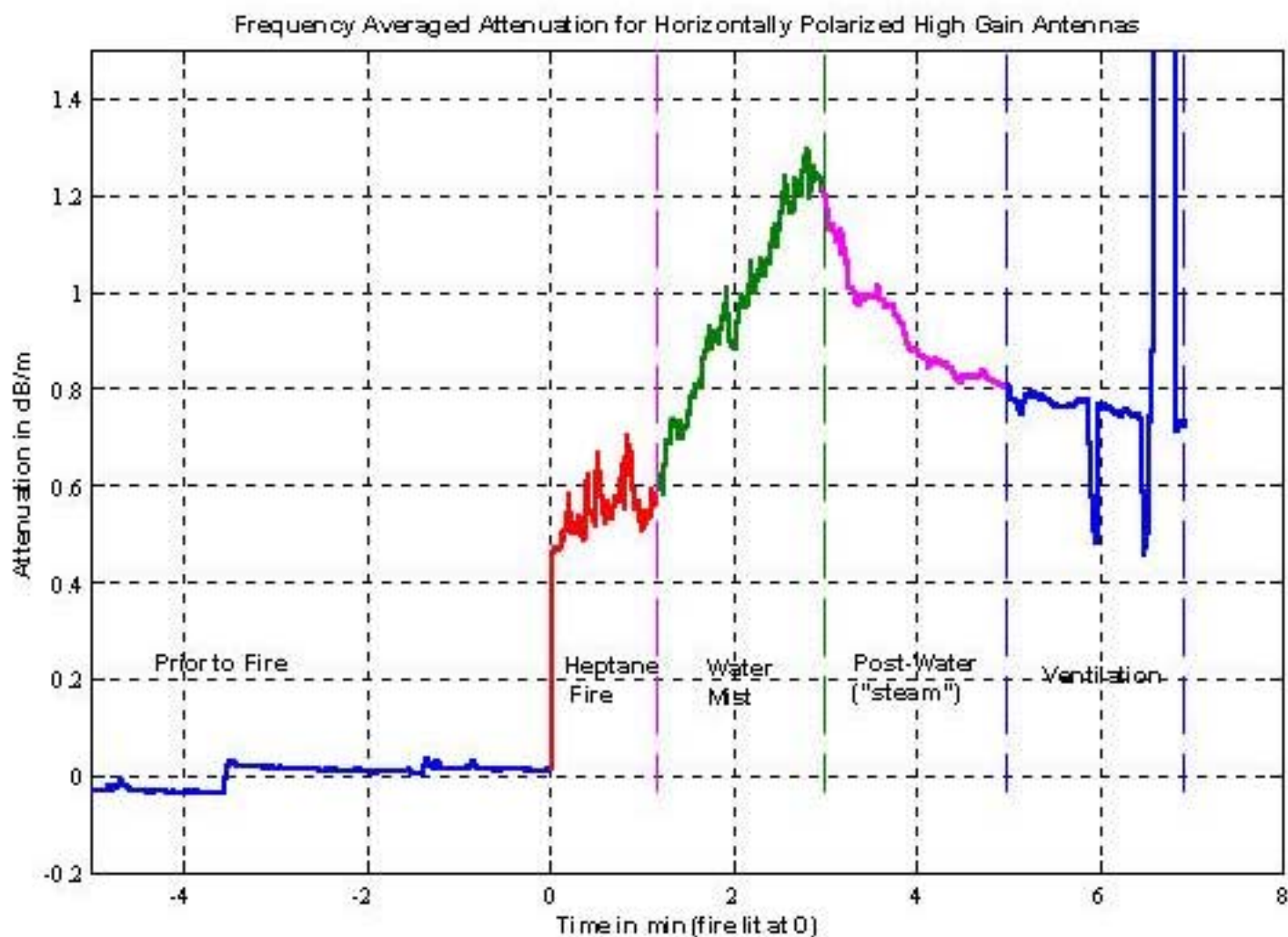
Ex-USS Shadwell Fourth Deck



General view of fourth deck

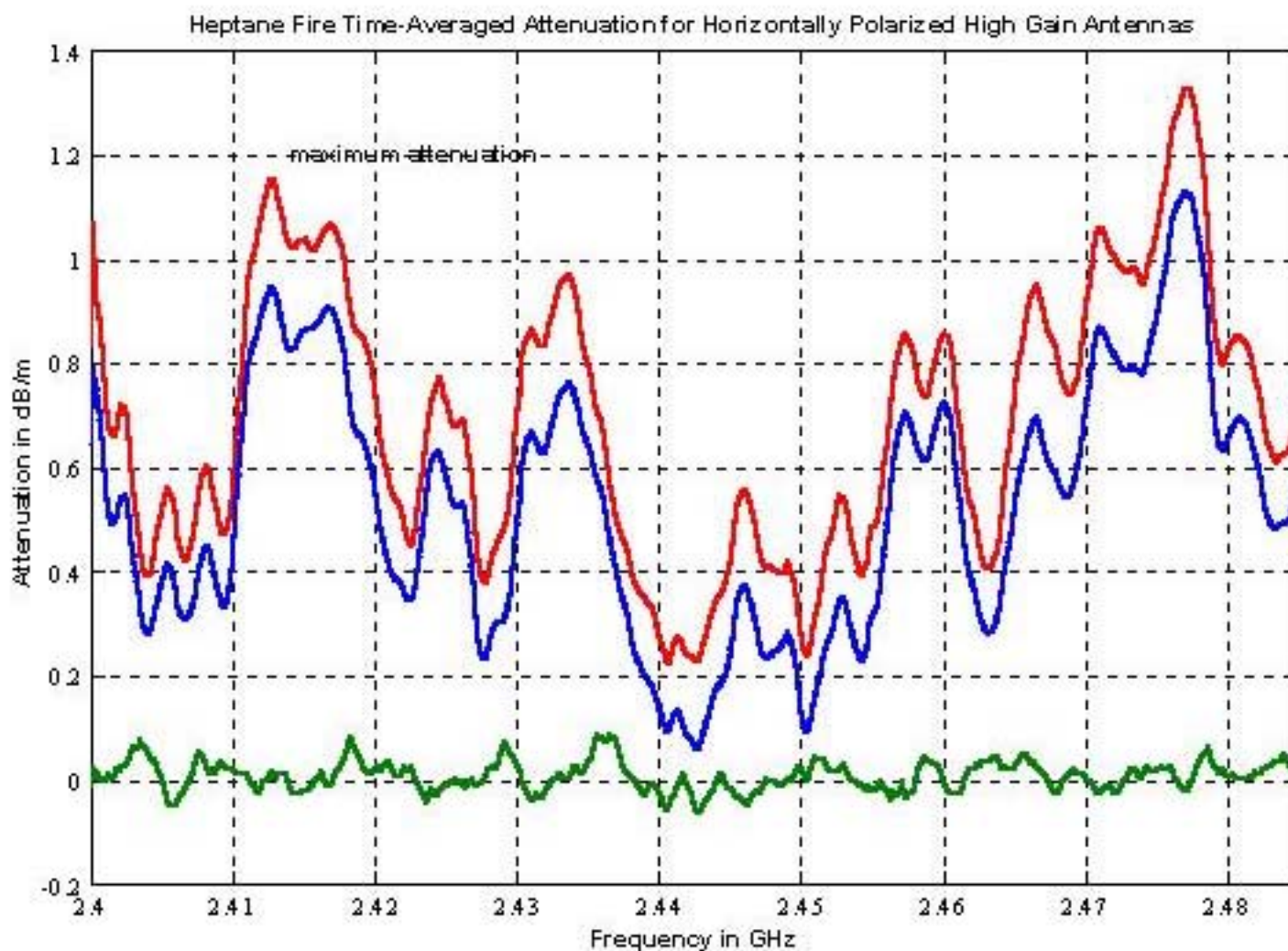


Frequency-Averaged Attenuation for Directional Antennas, H-Pol



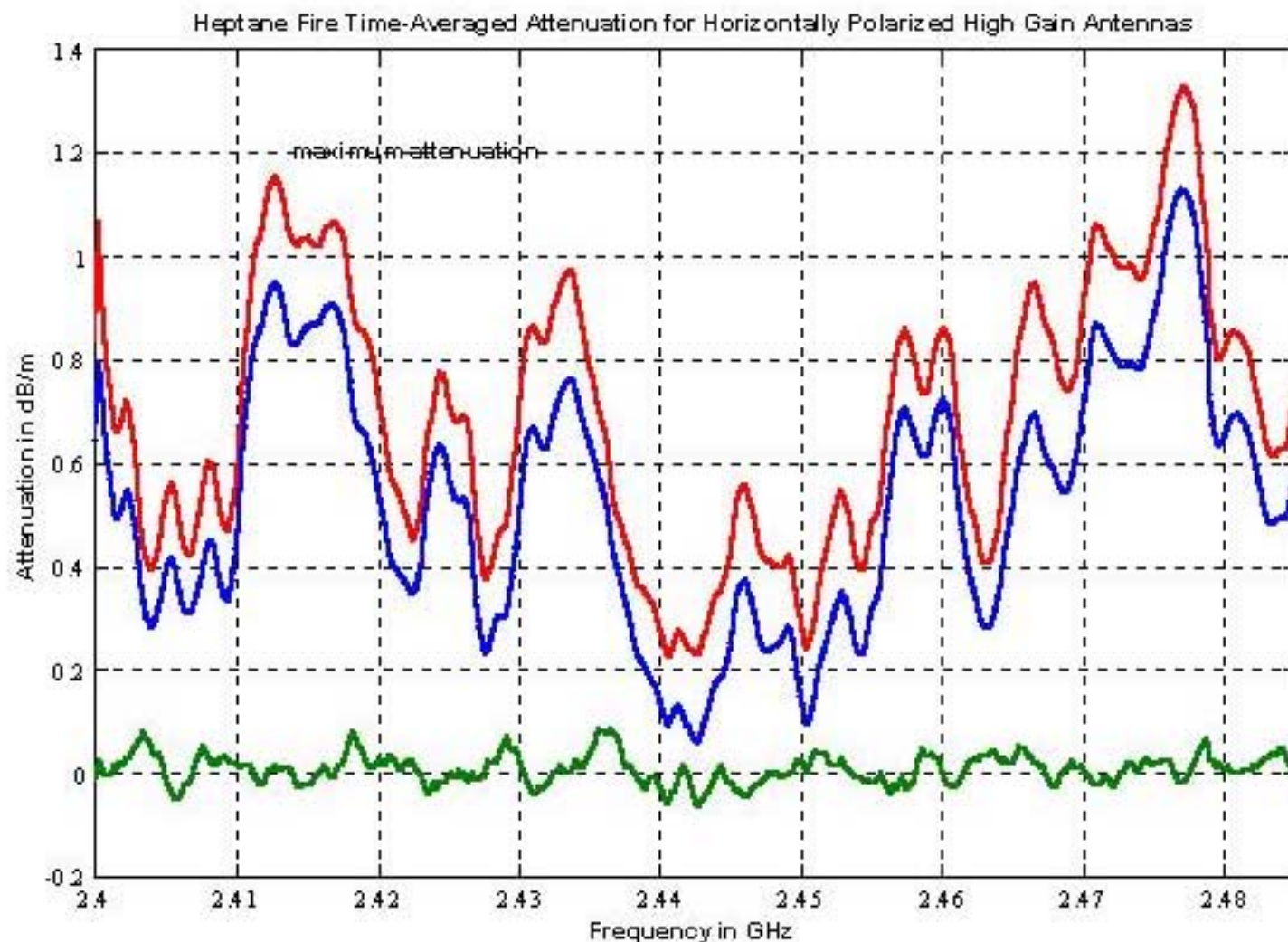


Heptane Fire Attenuation for Directional Antennas, H-Pol





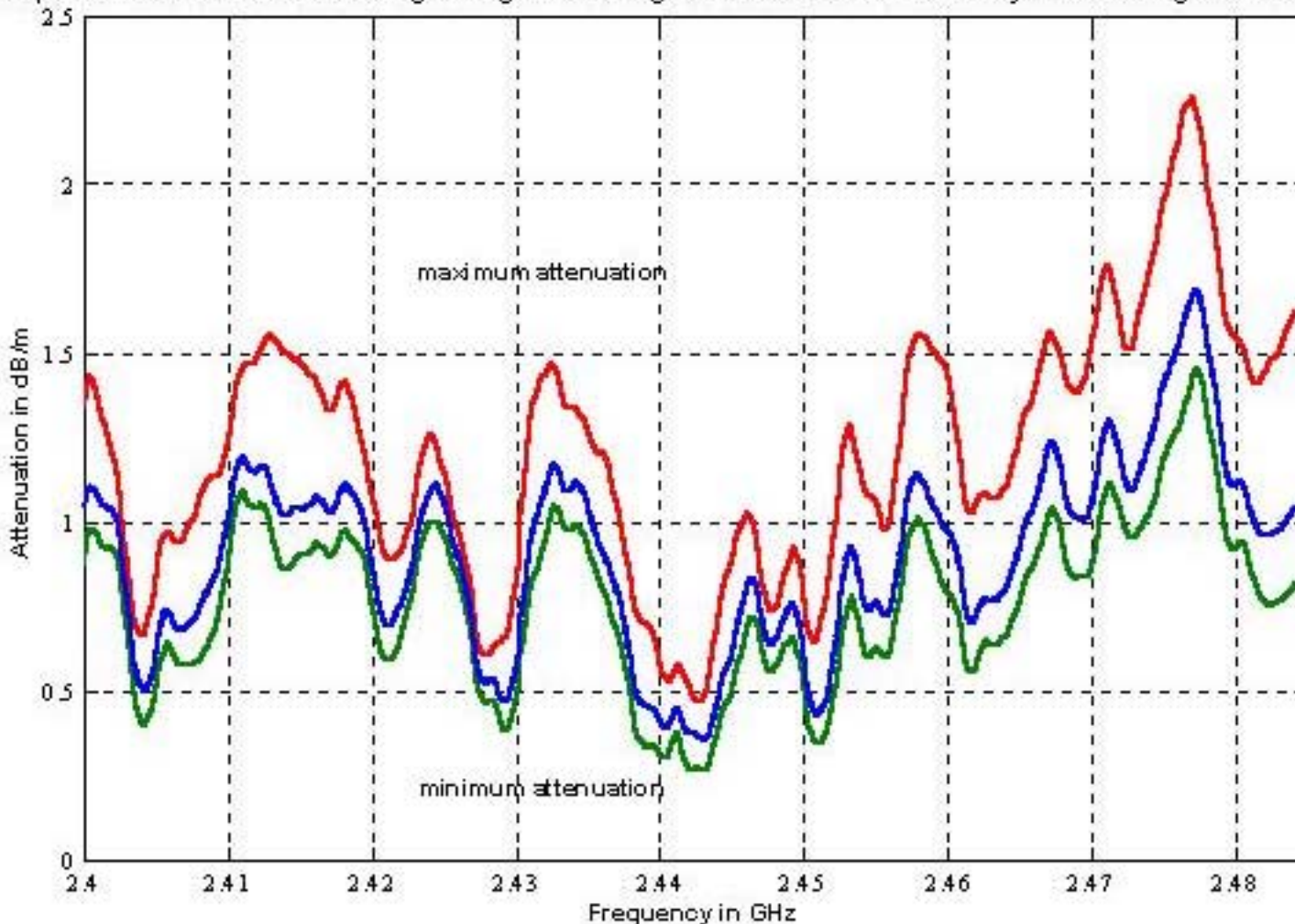
Water Mist Extinguishing Attenuation for Directional Antennas, H-Pol





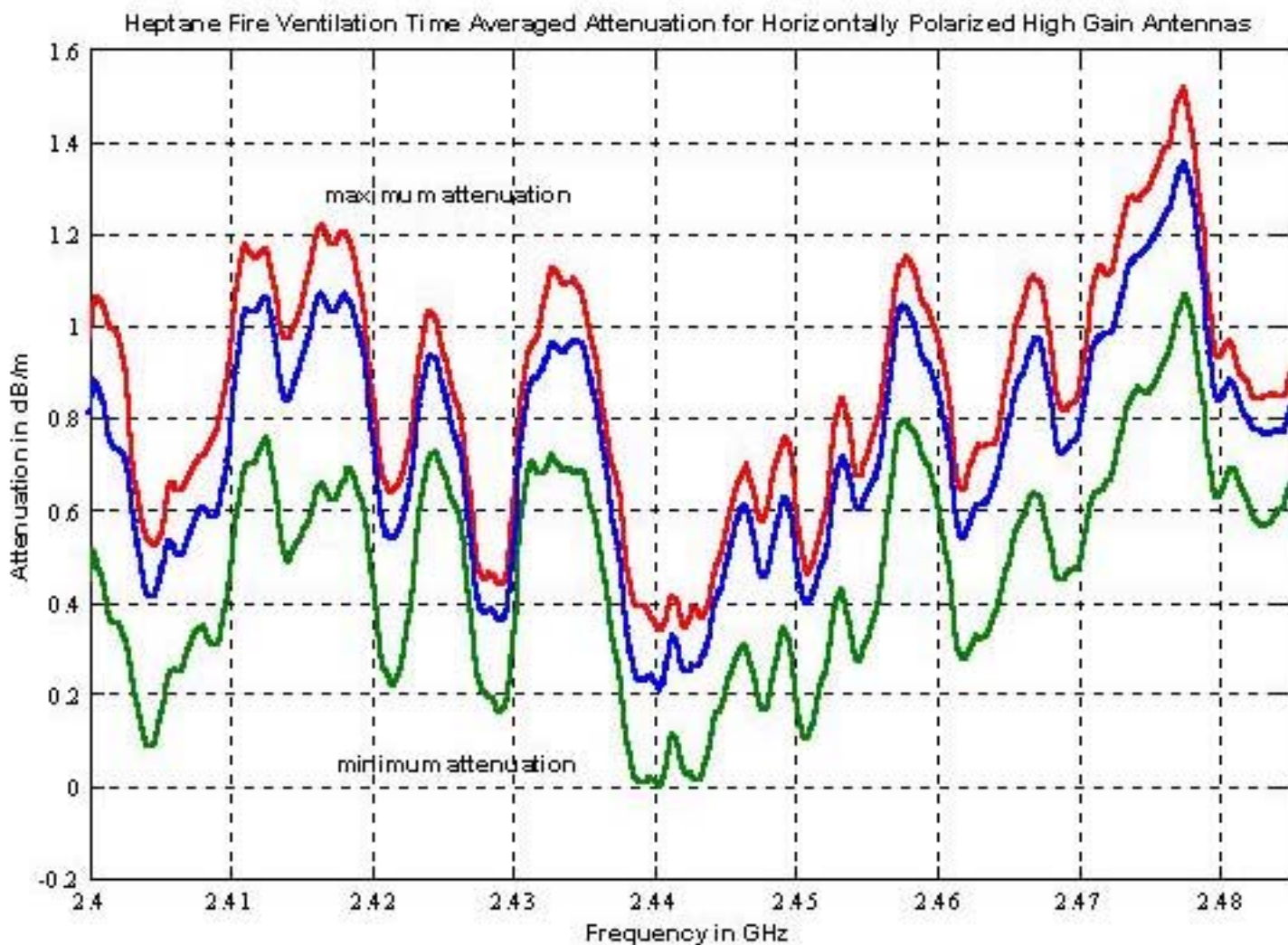
Post-Water Mist Extinguishing Attenuation for Directional Antennas, H-Pol

Heptane Fire Post-Water Mist Extinguishing Time Averaged Attenuation for Horizontally Polarized High Gain Antennas





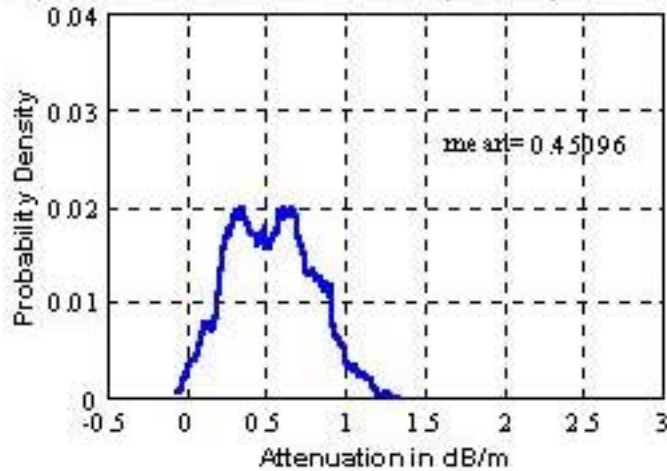
Ventilation Phase Attenuation for Directional Antennas, H-Pol



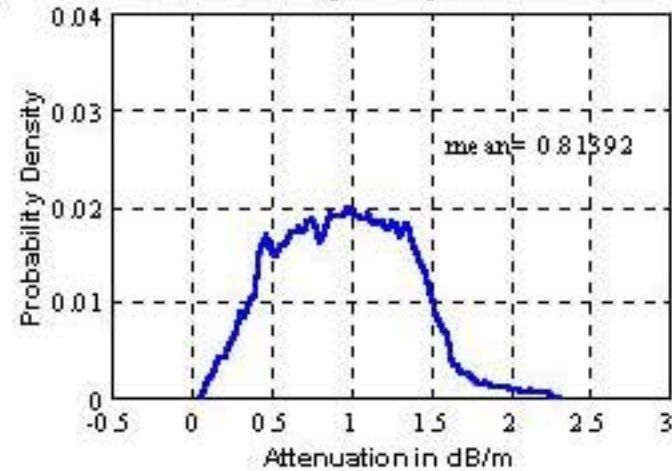


Attenuation Probability Density Functions for Directional Antennas, H-Pol

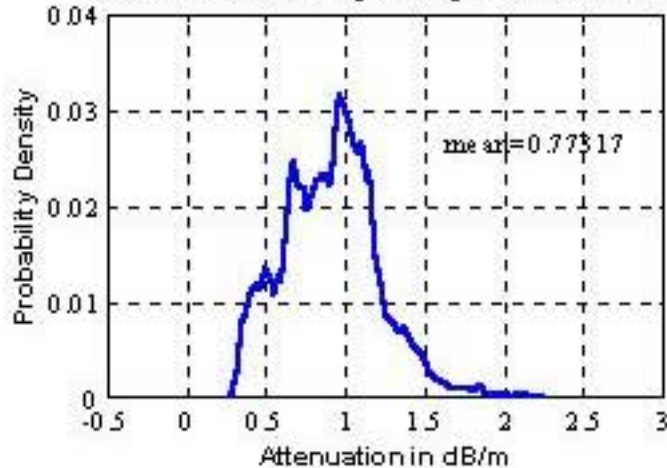
Heptane Fire Attenuation Probability Density Function (PDF)



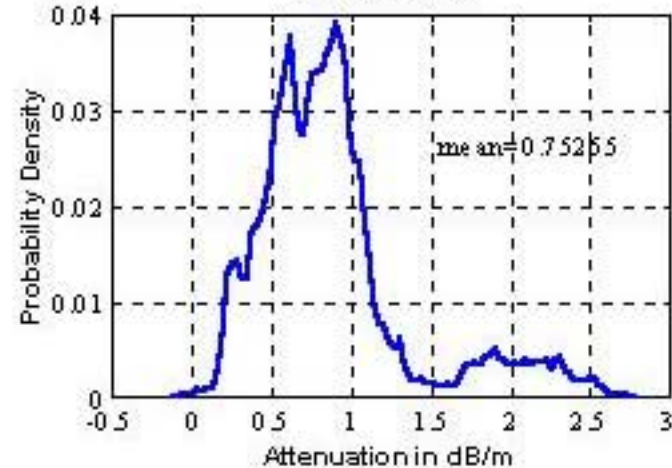
Water Mist Extinguishing Attenuation PDF



Post Water Mist Extinguishing Attenuation PDF

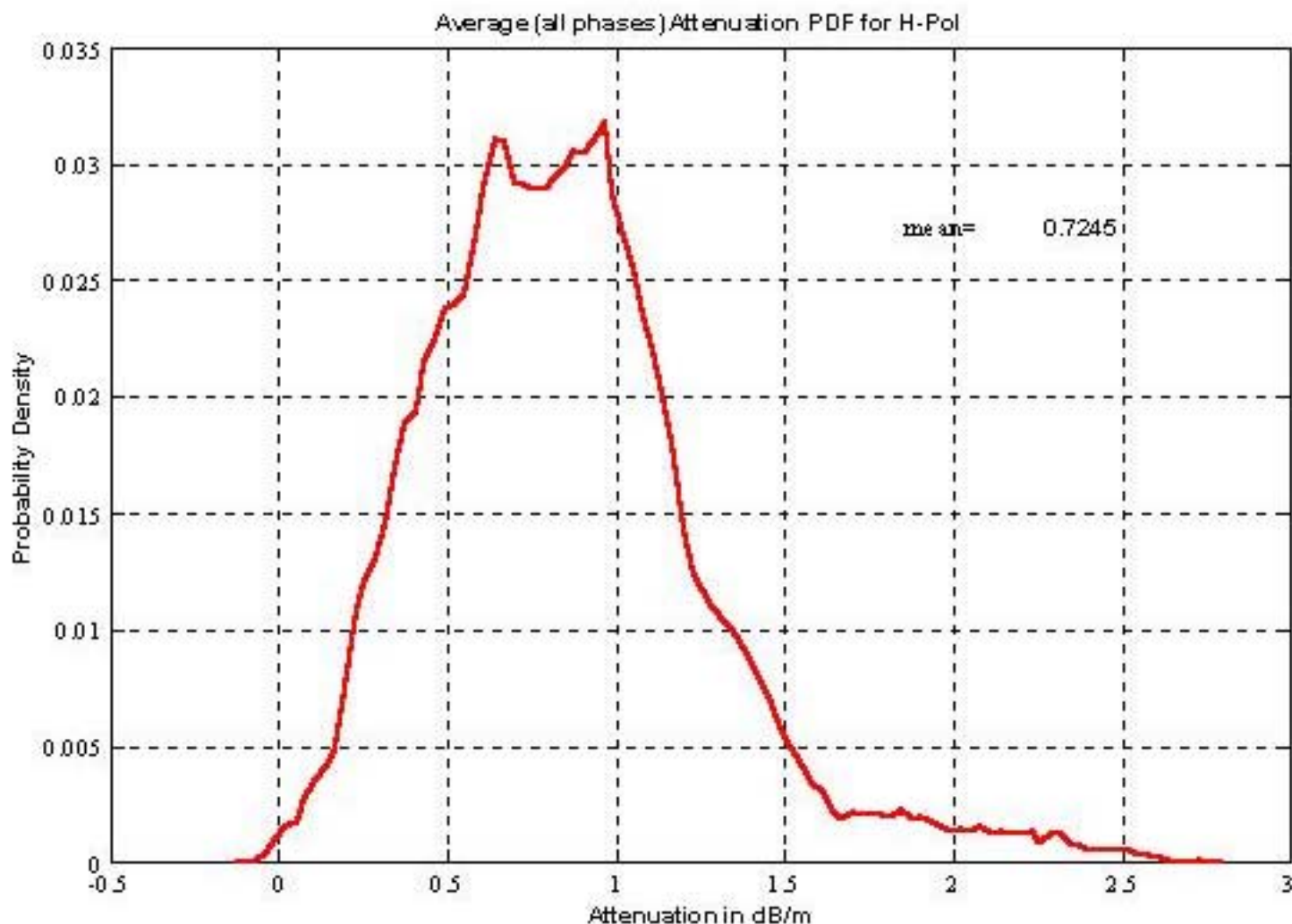


Ventilation PDF





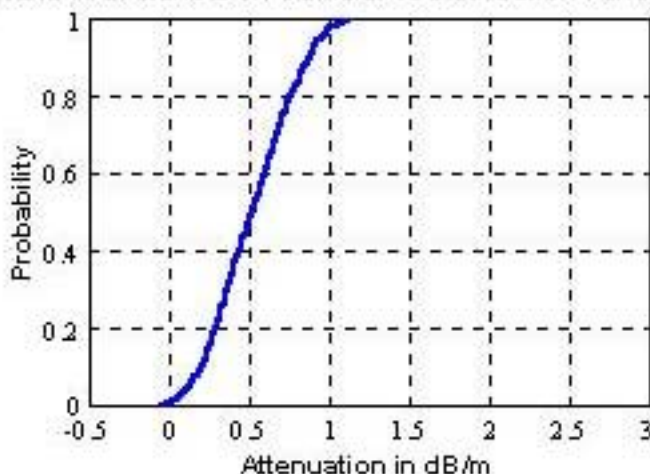
Average Attenuation Probability Density Function for Directional Antennas, H-Pol



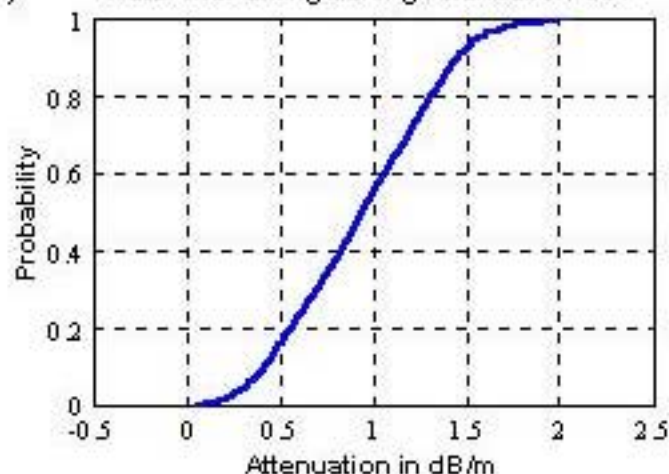


Attenuation Cumulative Distribution Functions for Directional Antennas, H-Pol

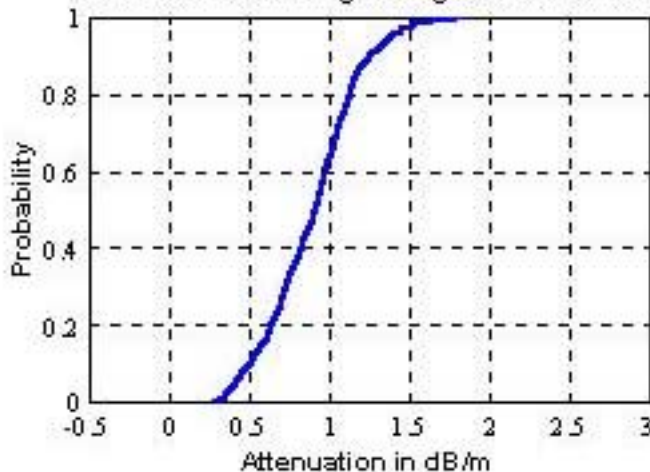
Heptane Fire Attenuation Cumulative Distribution Function (CDF)



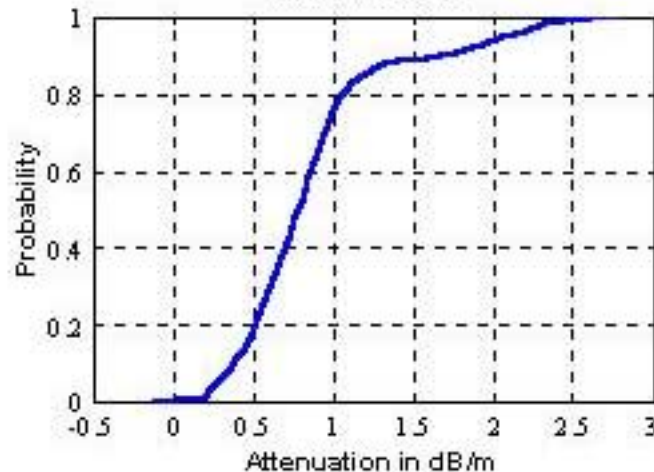
Water Mist Extinguishing Attenuation CDF



Post-Water Mist Extinguishing Attenuation CDF

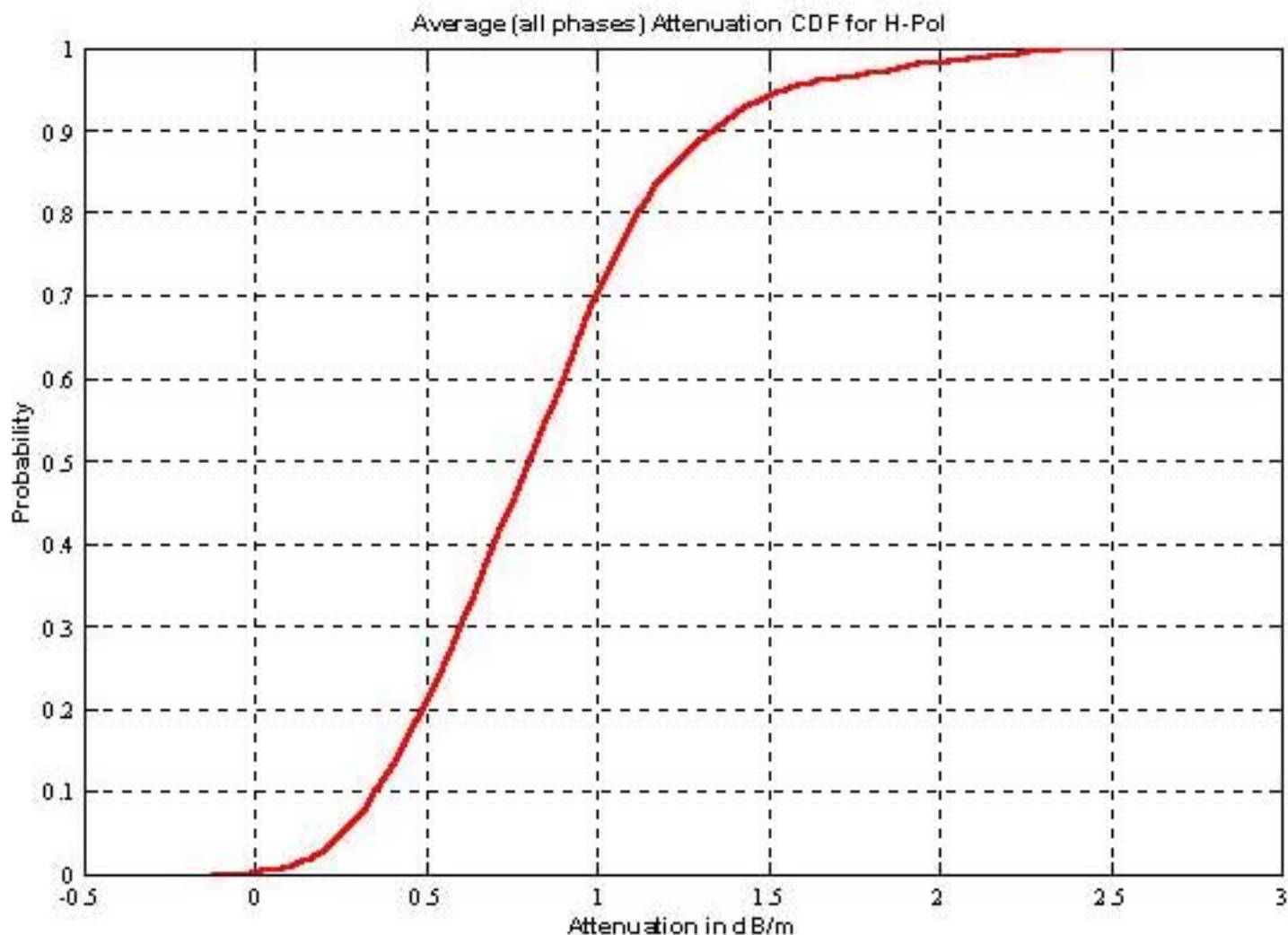


Ventilation CDF



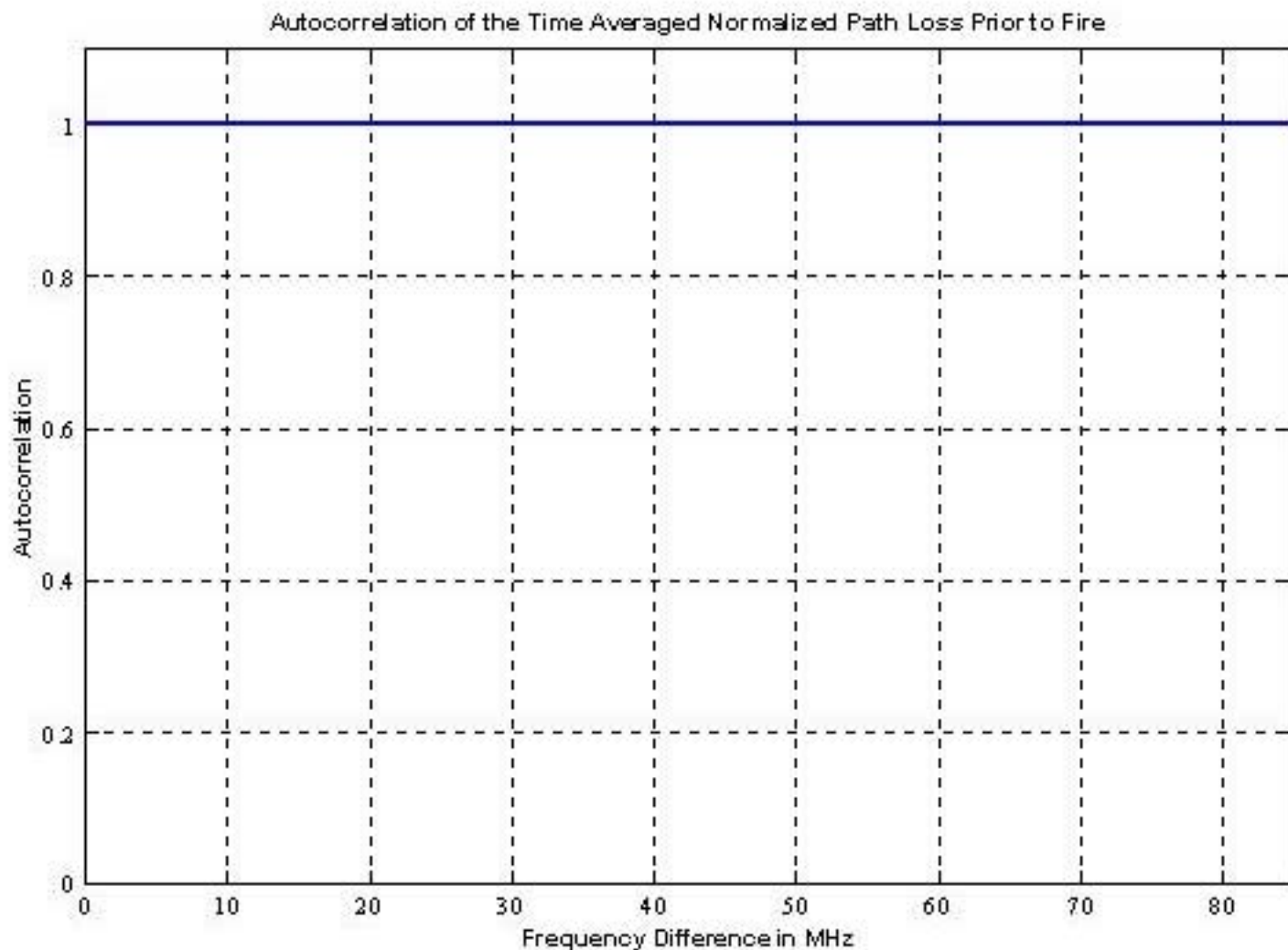


Average Attenuation Cumulative Distribution Function for Directional Antennas, H-Pol



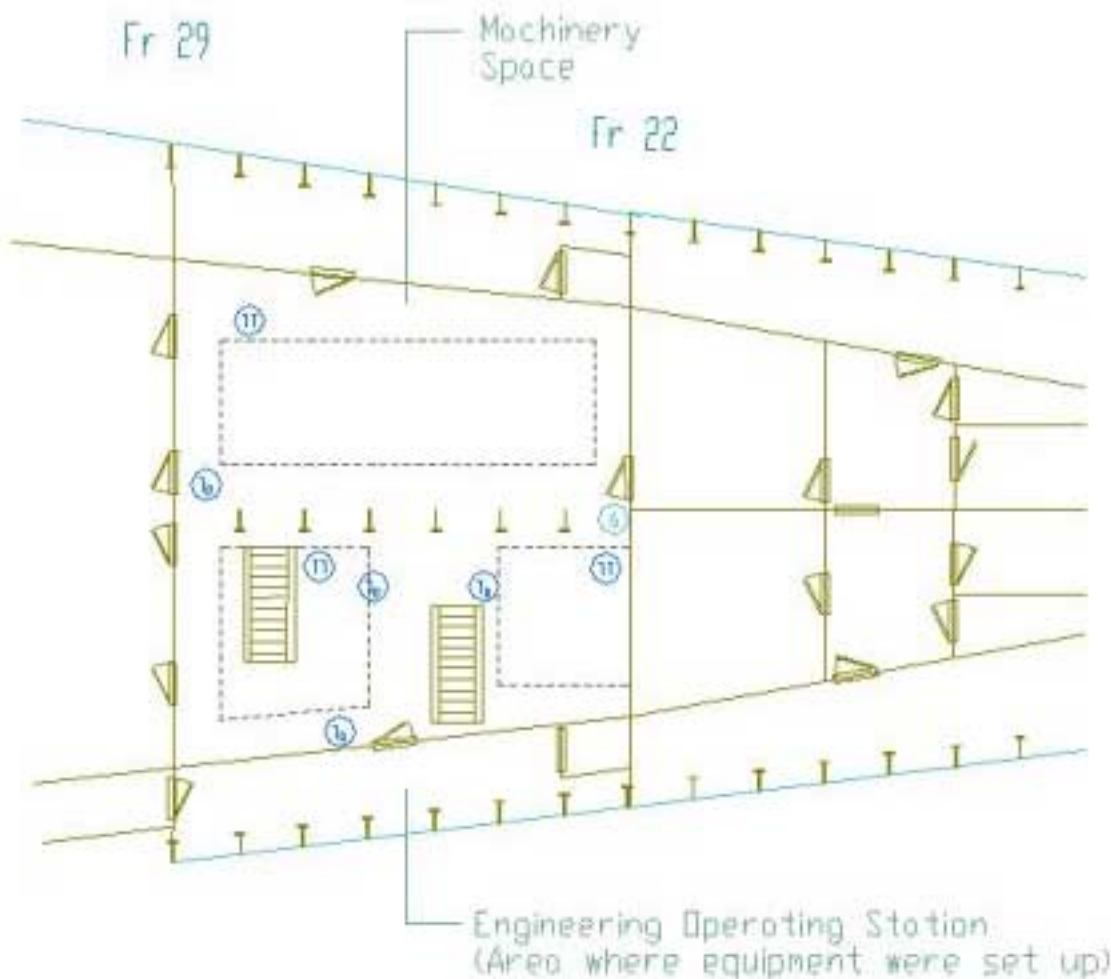


Normalized Autocorrelation Function for Directional Antennas Prior to Fire, H-Pol





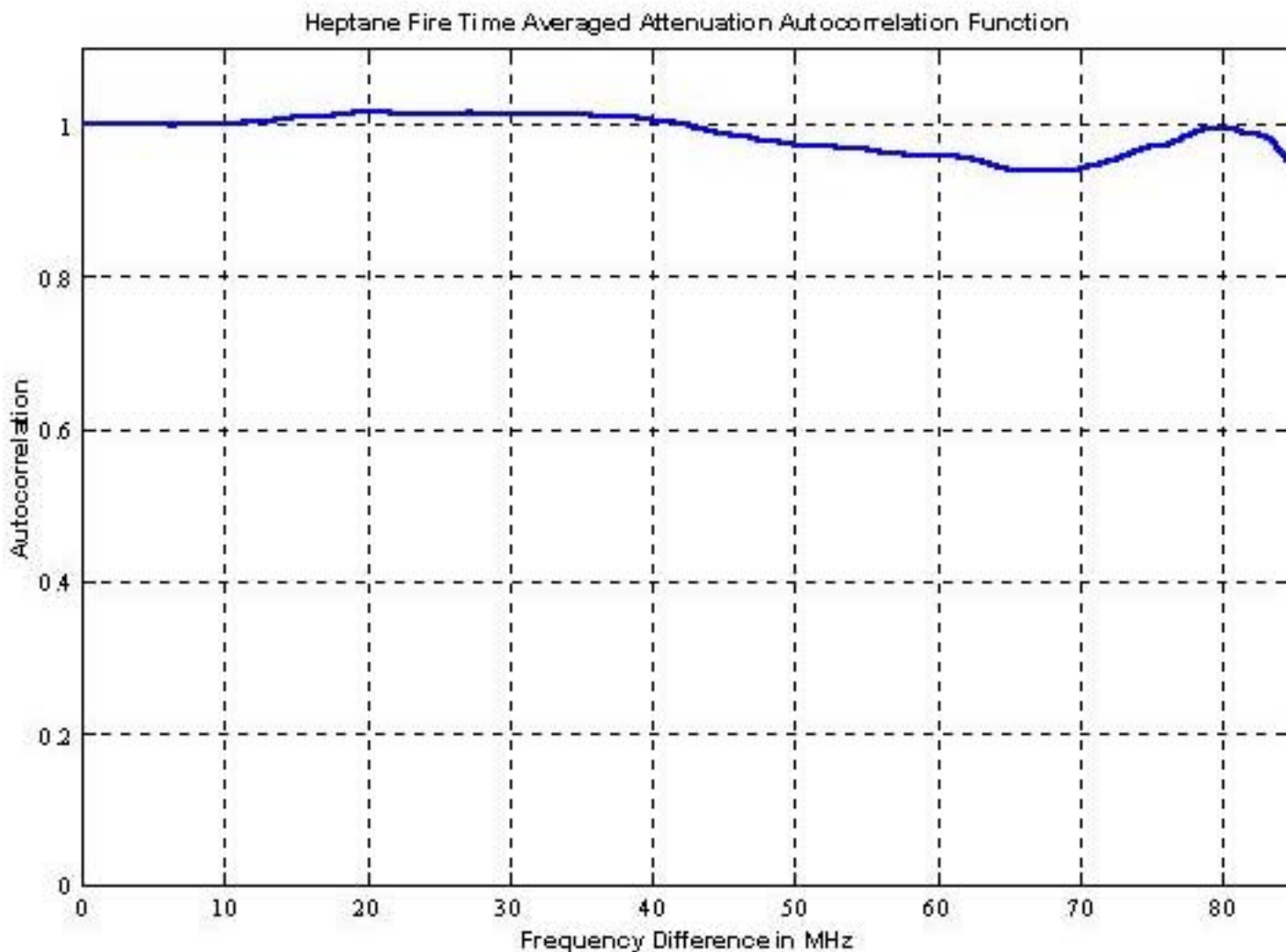
"Simulated" Machinery Space



Upper level instrumentation locations

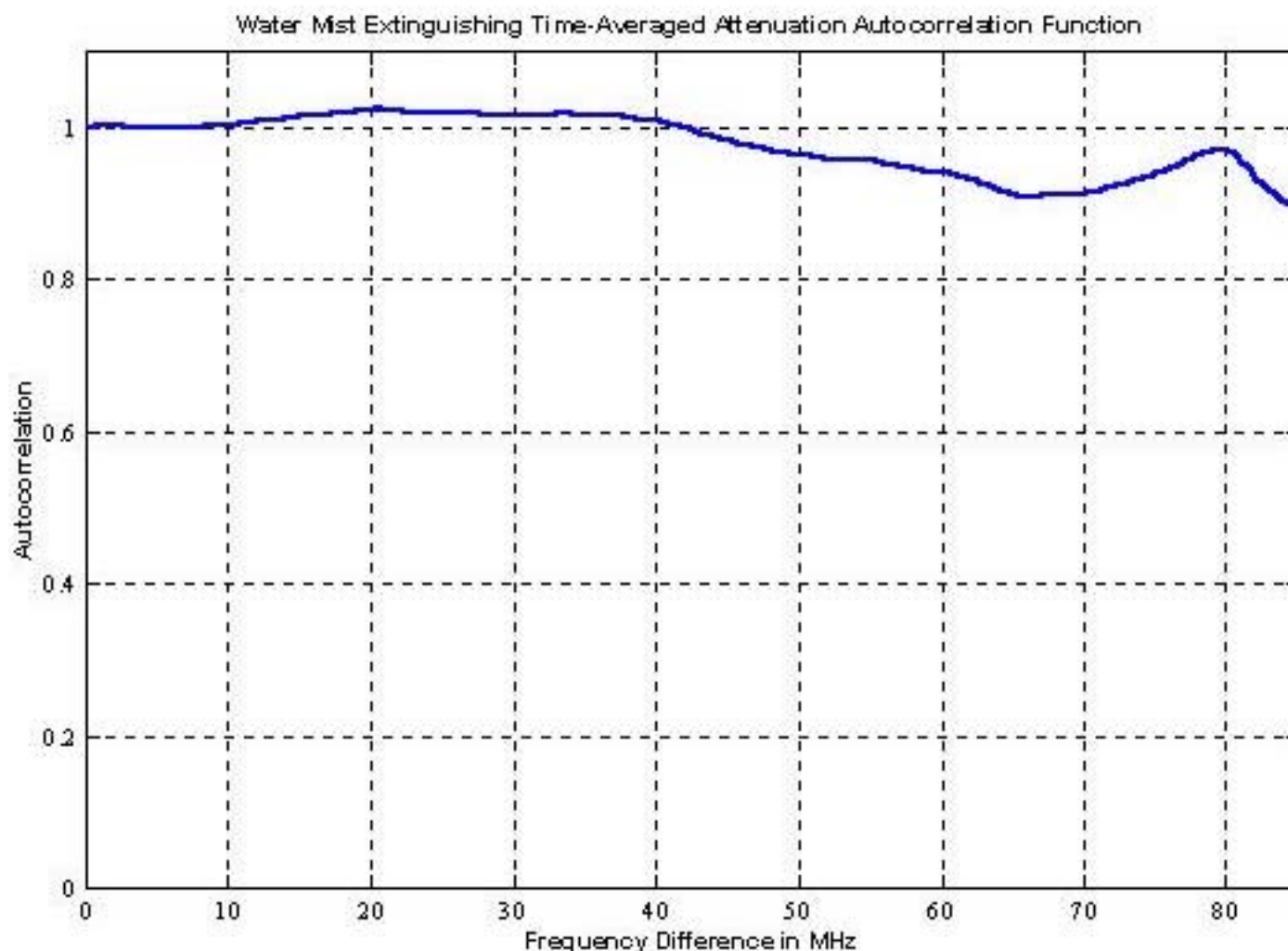


Heptane Fire Normalized Autocorrelation Function for Directional Antennas, H-Pol



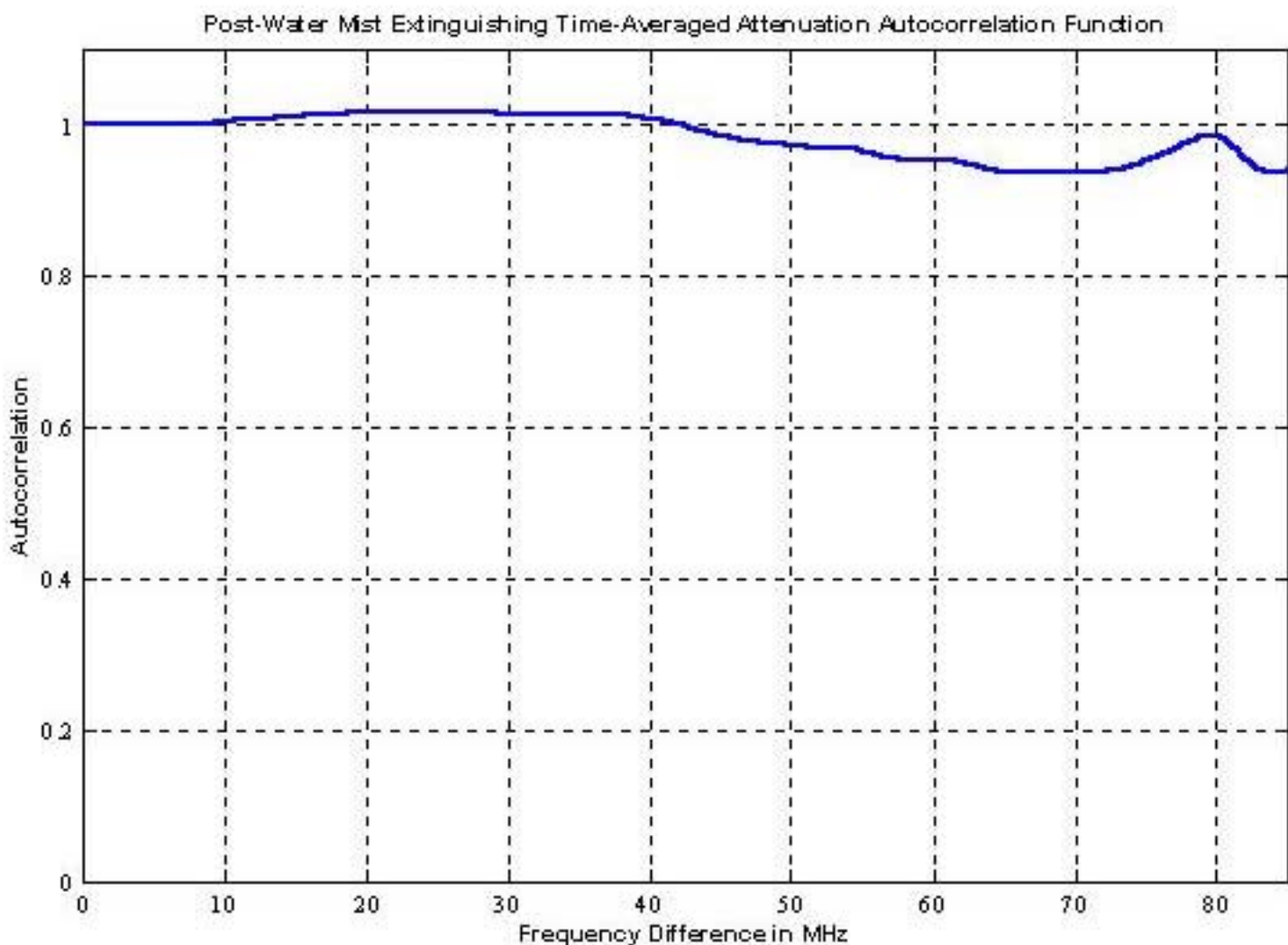


Water Mist Extinguishing Normalized Autocorrelation Function for Directional Antennas, H-Pol



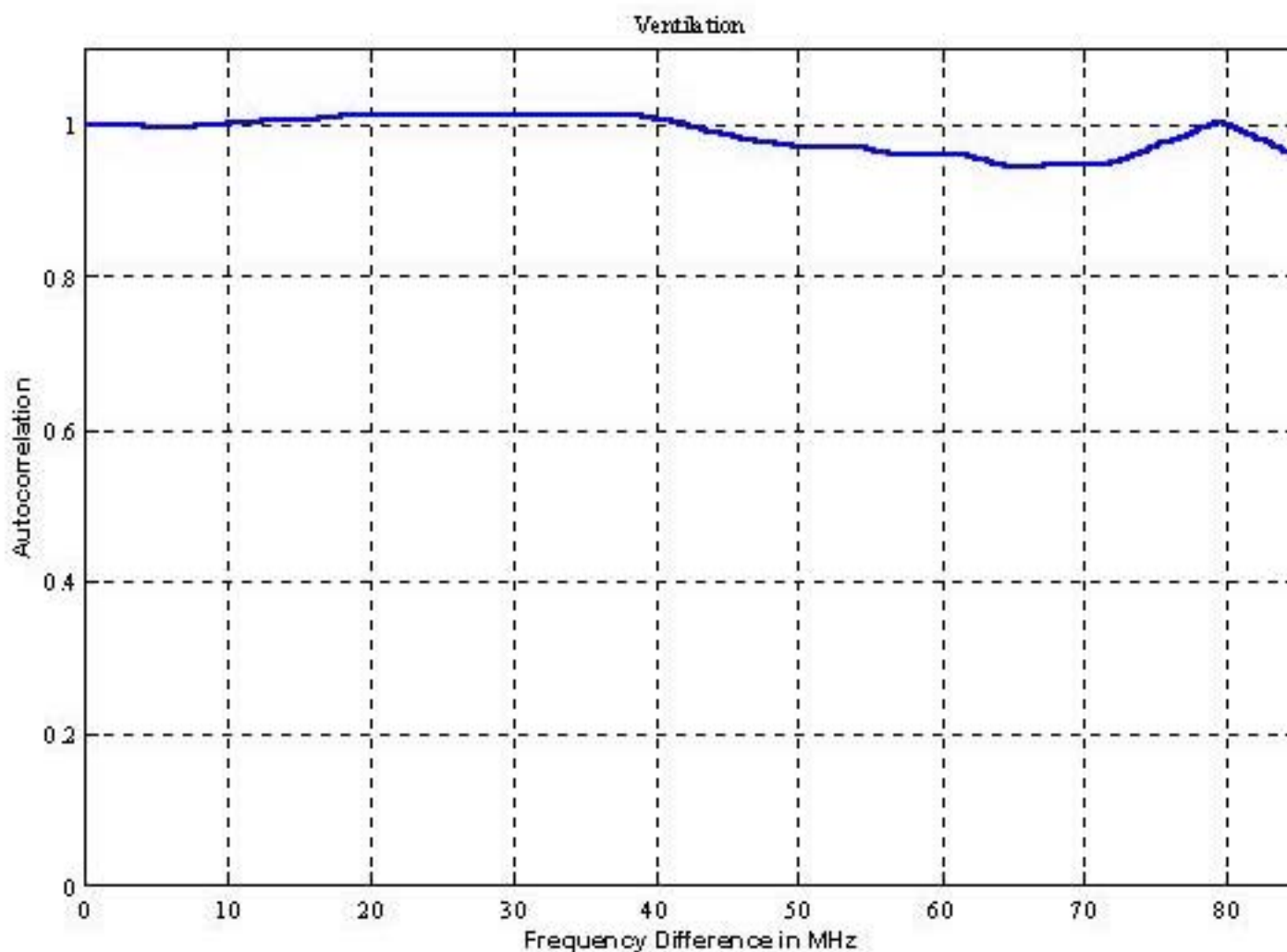


Post-Water Mist Extinguishing Normalized Autocorrelation Function for Directional Antennas, H-Pol





Ventilation Phase Normalized Autocorrelation Function for Directional Antennas, H-Pol





Conclusions



Conclusions

- The effects of fire and water mist fire extinguishing are profoundly different for directional (high gain) and non-directional (low gain) antennas
- The difference is caused by the prevalence of a single, direct path for the directional antennas as opposed to the multipath propagation for the non-directional antennas



Conclusions for Directional Antennas

- The attenuation per unit length for directional antennas exhibits relatively small variations with time and frequency
- The attenuation due to water mist extinguishing is substantially larger than the attenuation due to the fire itself



Conclusions for Directional Antennas

- The average (includes fire and water mist extinguishing) attenuation in the entire 2.4 GHz ISM band for the two linear polarizations and **diesel** fire:
- **0.69 dB/m** for vertical
- **0.54 dB/m** for horizontal
- with almost 100% of the values in the 0 to 2 dB/m range



Conclusions for Directional Antennas

- The **heptane** fire average (includes fire and water mist extinguishing) attenuation in the entire 2.4 GHz ISM band for the two linear polarizations:
- **0.33 dB/m** for vertical
- **0.72 dB/m** for horizontal
- with almost 100% of the values in the -0.5 to 3 dB/m range



Conclusions for Non-Directional Antennas

- The average attenuation for non-directional antennas is comparable to the average attenuation for the directional antennas but the values for the non-directional antennas cover an order of magnitude larger range (30 dB vs 2 dB)
- The fire and water mist extinguishing system cause the communication link to experience rapid and severe fluctuations ("fading")



Instrumentation Space





Conclusions for Non-Directional Antennas

- The average (includes fire and water mist extinguishing) attenuation in the entire 2.4 GHz ISM band for the two linear polarizations and **diesel** fire:
- **0.76 dB/m** for vertical
- **0.66 dB/m** for horizontal
- with almost 100% of the values in the -10 to +20 dB/m range



Recommendations

- The measurements indicate that the effect of a ship compartment fire and the water mist fire extinguishing can be modelled as rapid, frequency selective fading with relatively small average value of signal loss (the probability of signal gain is slightly smaller than the probability of signal loss) but with signal losses up to 20 dB possible



Recommendations

- Directional antennas are an effective countermeasure to the fire/water mist induced fading
- Frequency diversity will reduce the fading but not to the extent that directional antennas would
- It would be of interest to measure the effects of fire/water mist on circularly polarized antennas

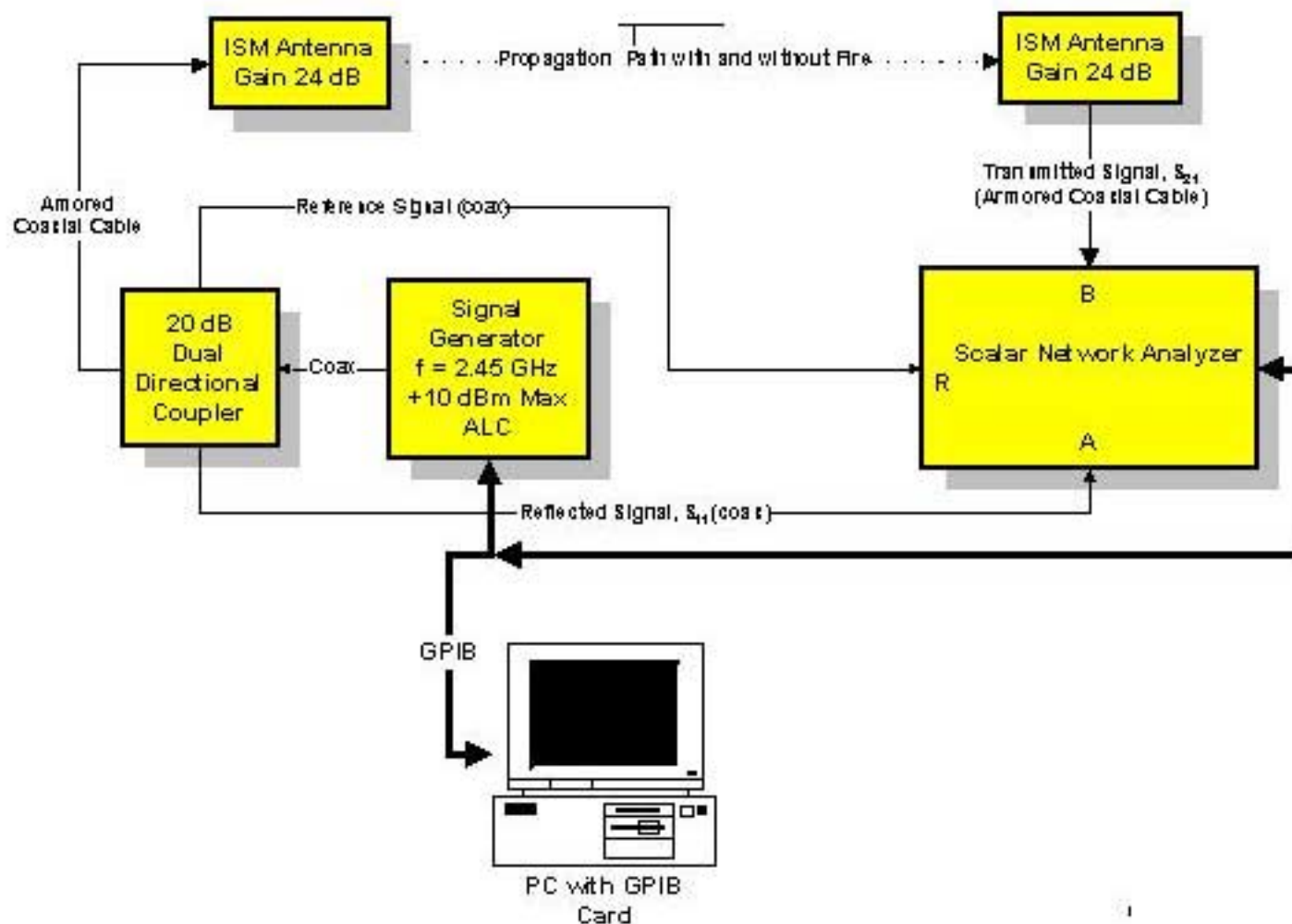


Measurement Space



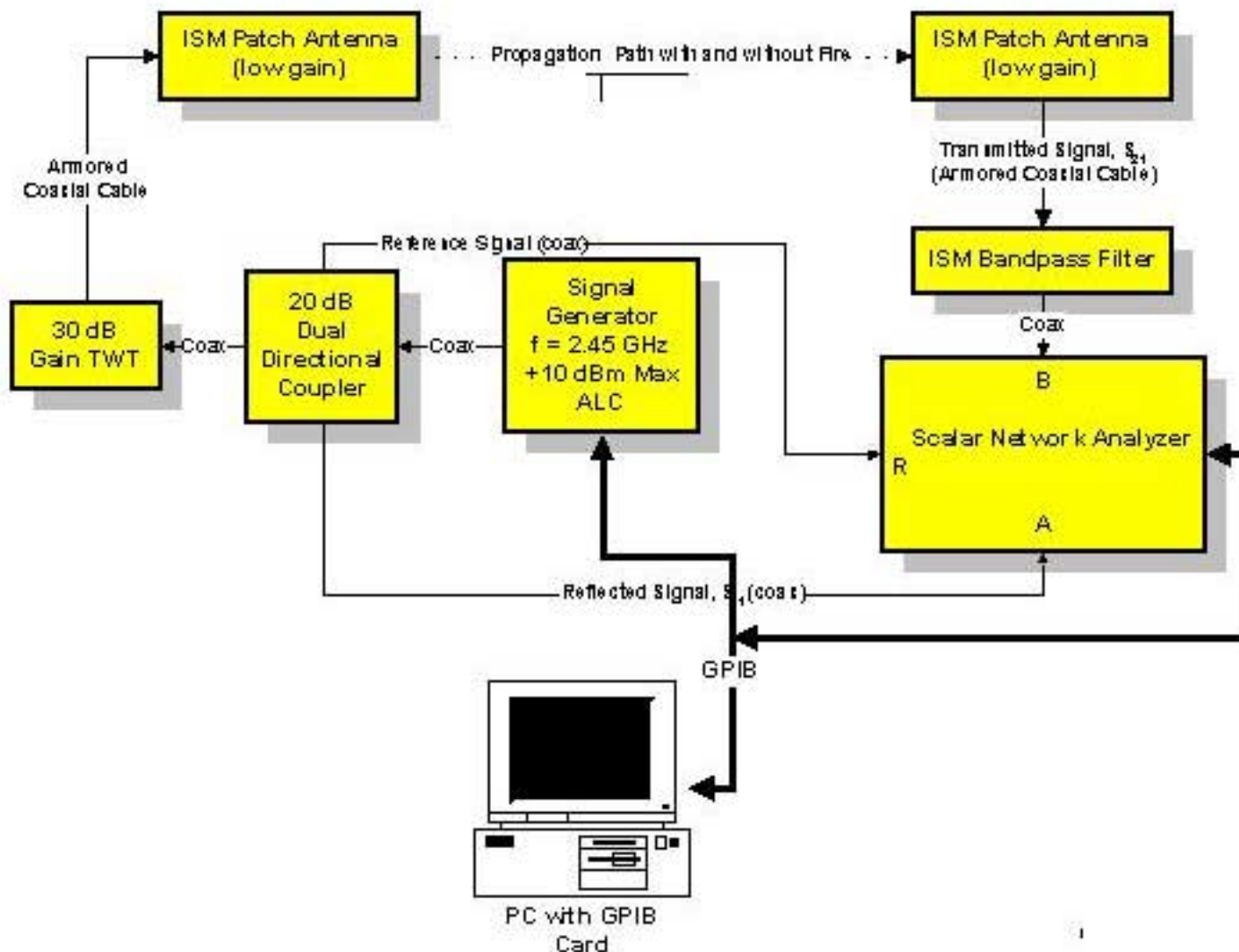


High Gain Antenna Measurement Setup



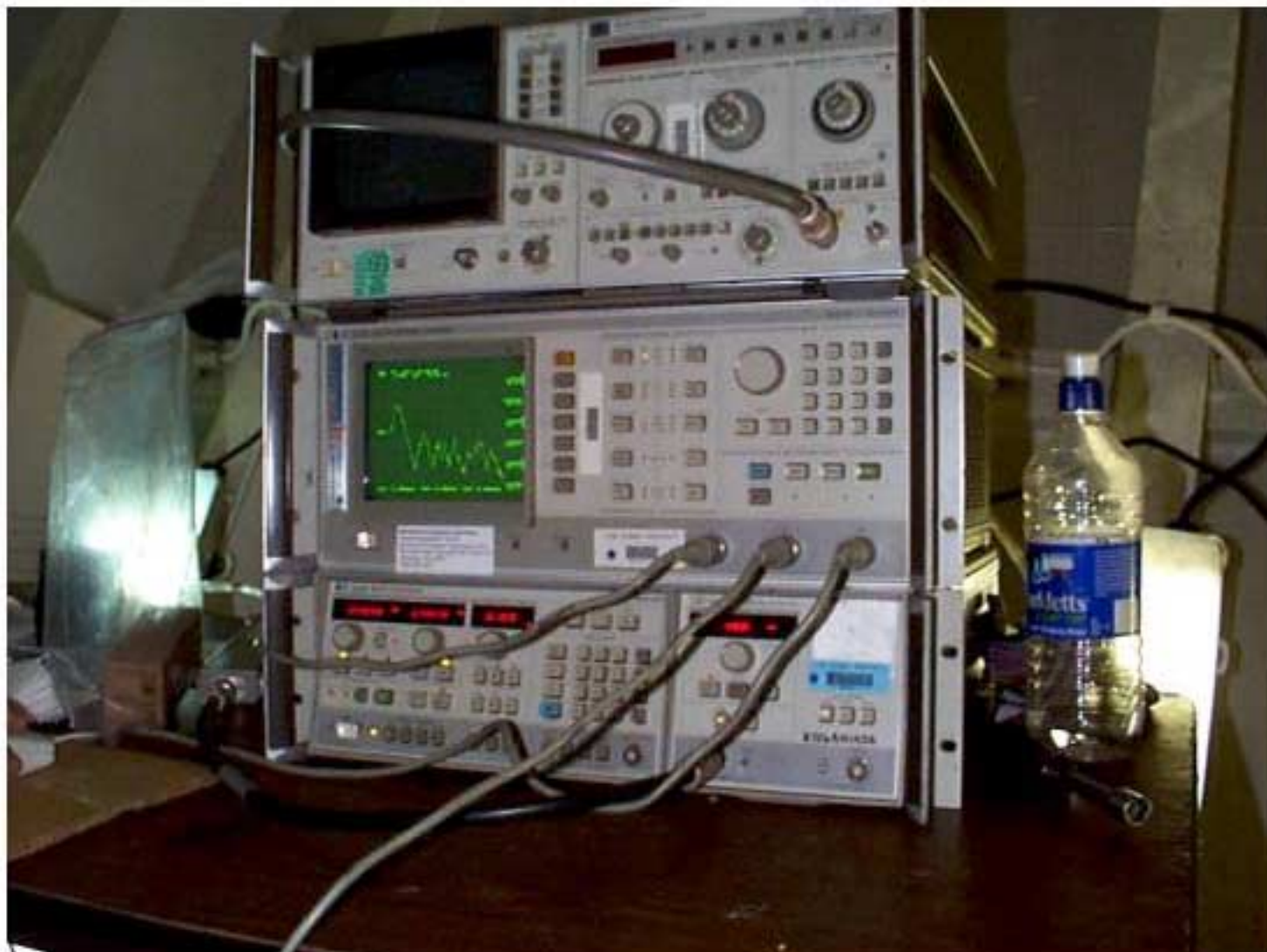


Low Gain Antenna Measurement Setup





Network and Spectrum Analyzer Setup



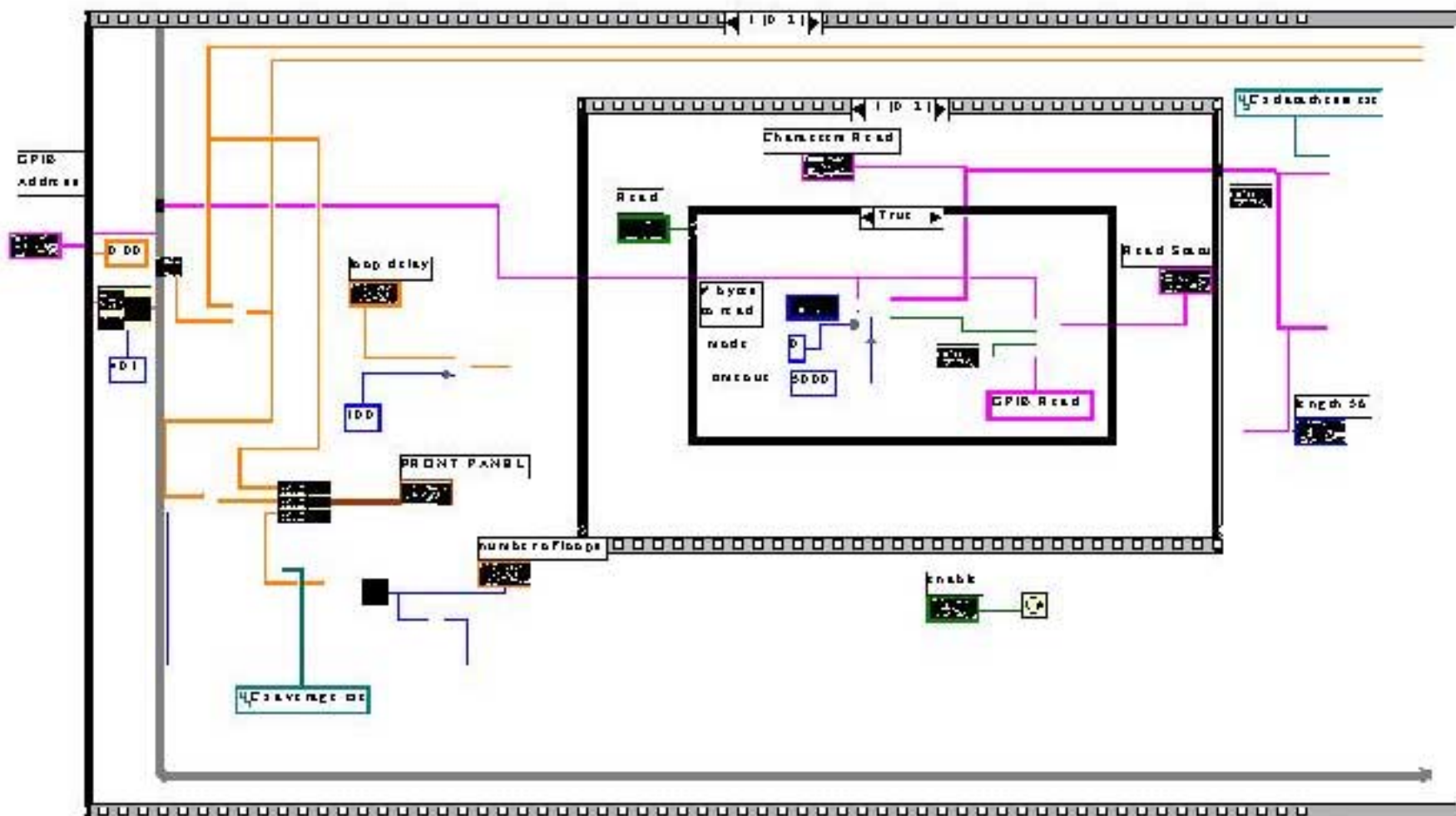


PC "Controller" and the TWT





Network Analyzer LabView Driver



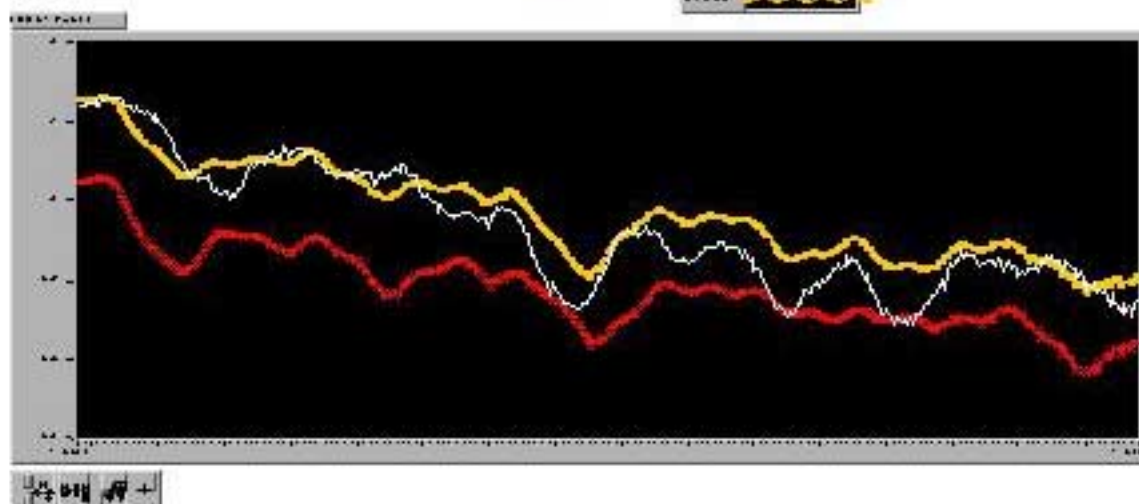
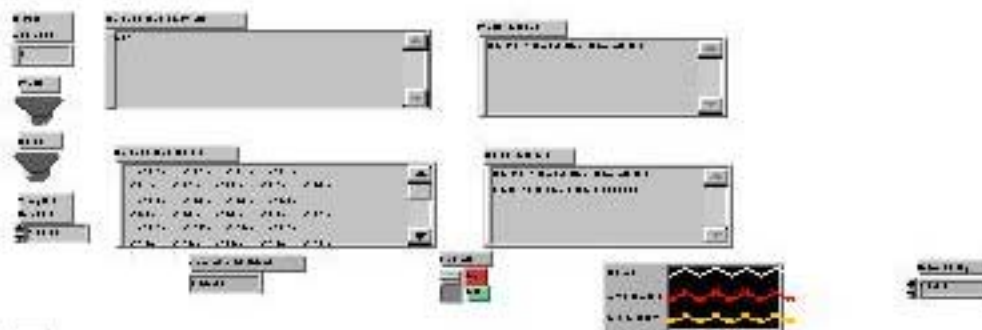


Contents

- Objective
- Measurements
- Results
- Conclusions



LabView "Front Panel"

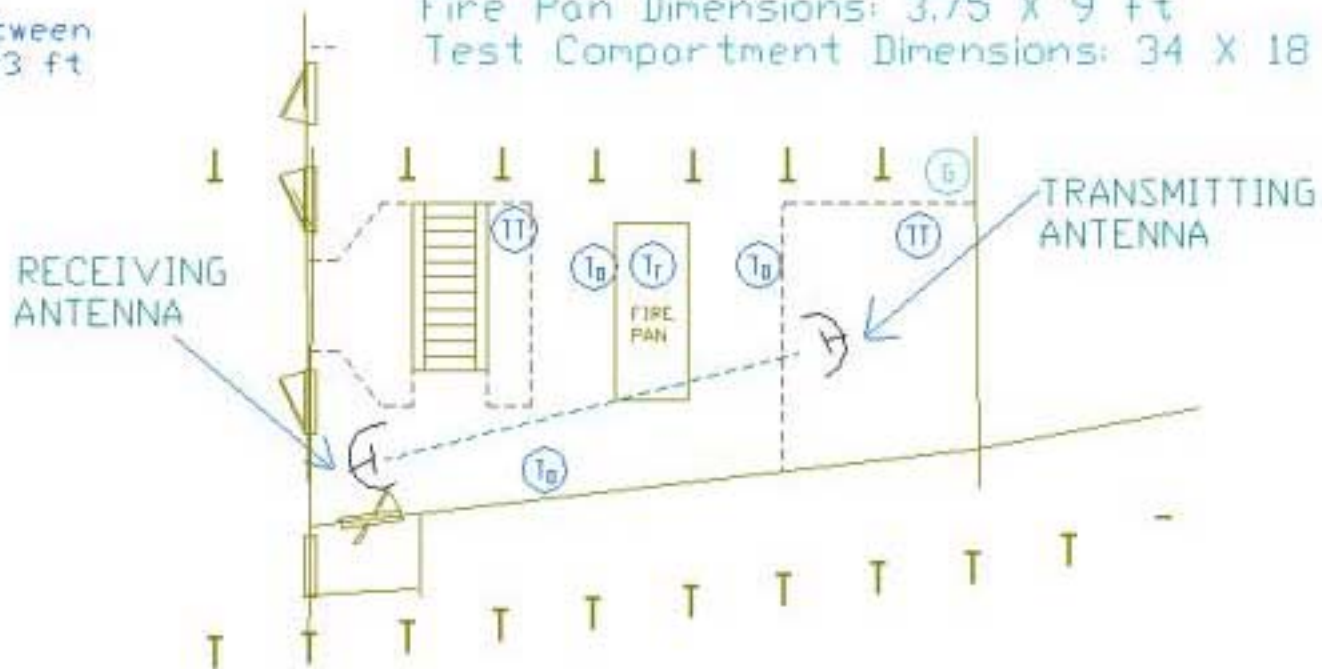




Test Antenna Locations

Distance between
Antennas 23 ft

Fire Pan Dimensions: 3.75 X 9 ft
Test Compartment Dimensions: 34 X 18 ft



TEST COMPARTMENT DETAILS



Directional (high gain) Linearly Polarized Antenna





Directional (high gain) Linearly Polarized Antenna





Directional (high gain) Linearly Polarized Antenna





Non-Directional (low gain) Linearly Polarized Patch Antenna





View of Diesel Fire Shortly After It Was Lit





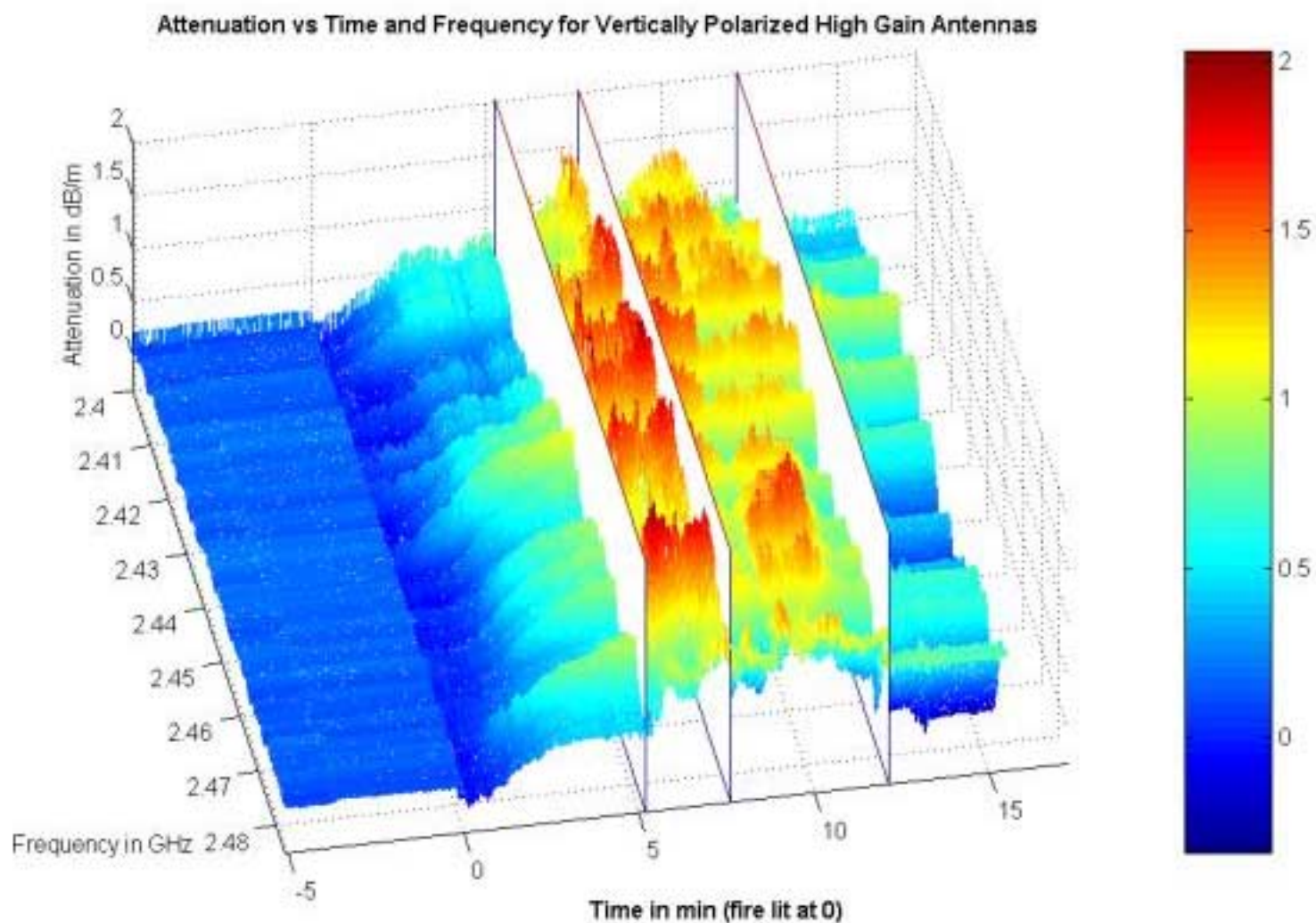
Results



Diesel Fire Results for Vertically Polarized Directional (High Gain) Antennas



Attenuation for Directional Antennas, V-Pol



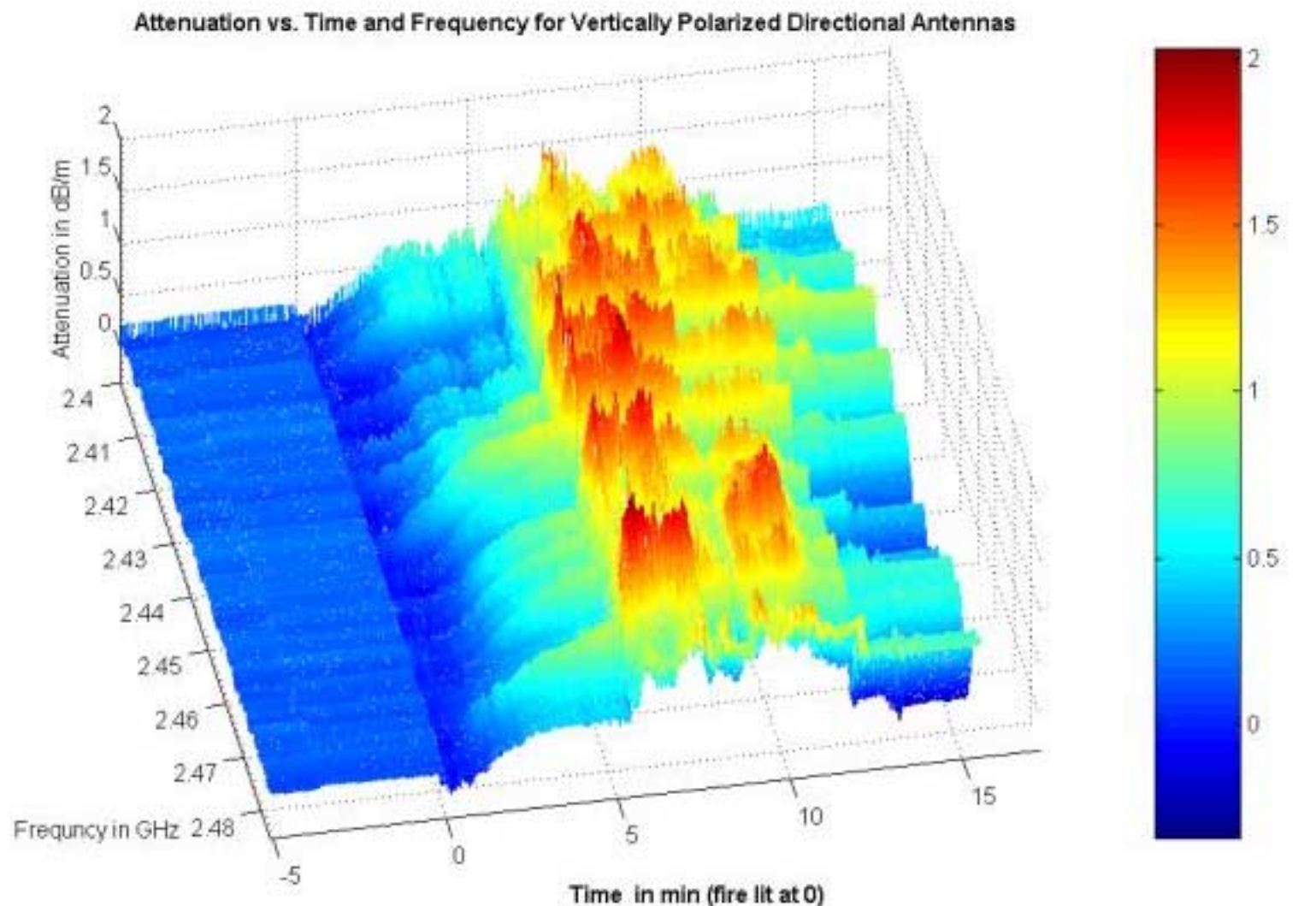


Objective

- The objective was to quantify experimentally the effects of ship compartment fuel fires (diesel and heptane) and the water mist fire extinguishing system on the propagation of RF signals in the 2.4 GHz to 2.485 GHz ISM frequency range using the ex-USS Shadwell fire research facilities operated by the Naval Research Lab

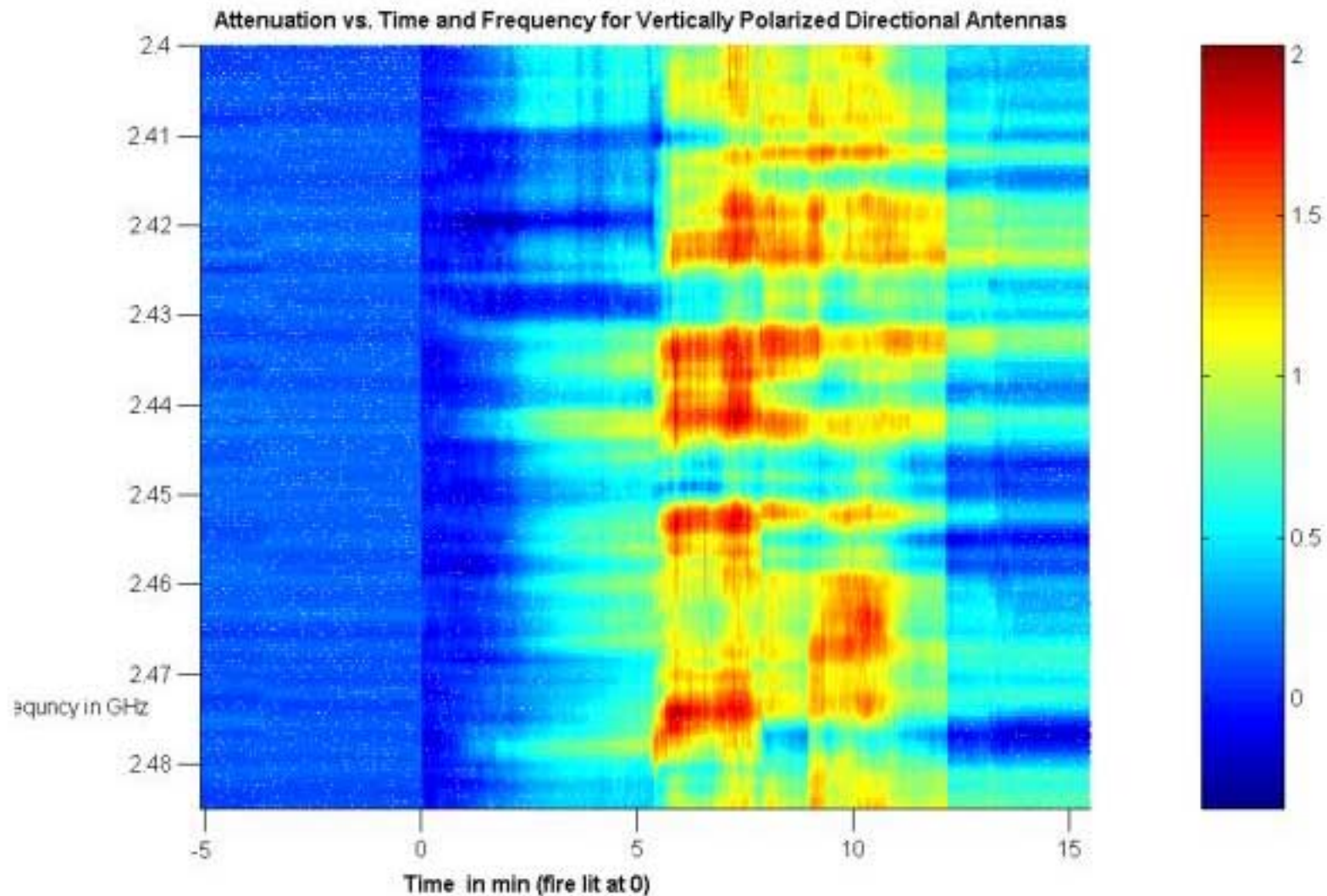


Attenuation for Directional Antennas, V-Pol



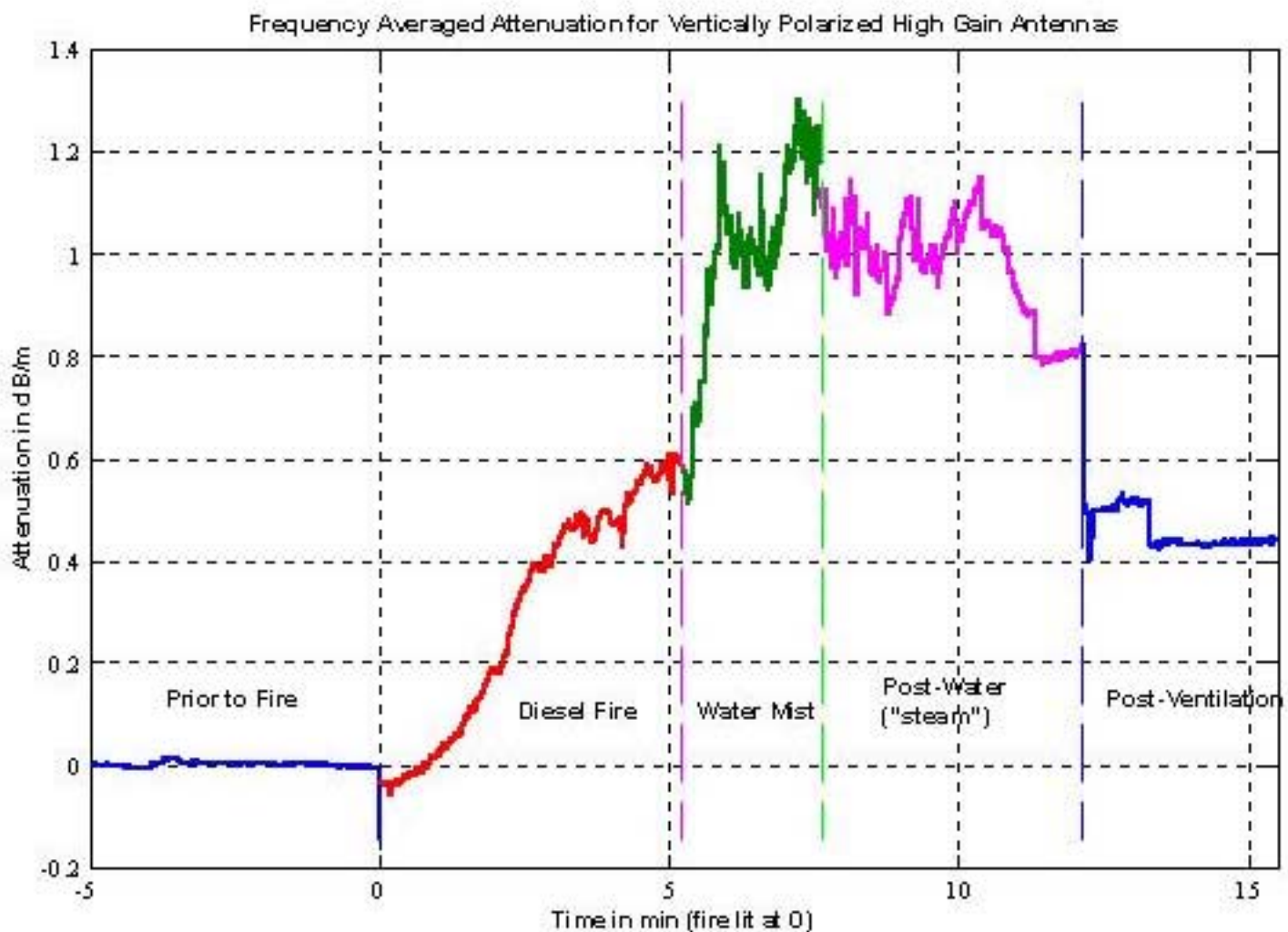


Attenuation for Directional Antennas, V-Pol



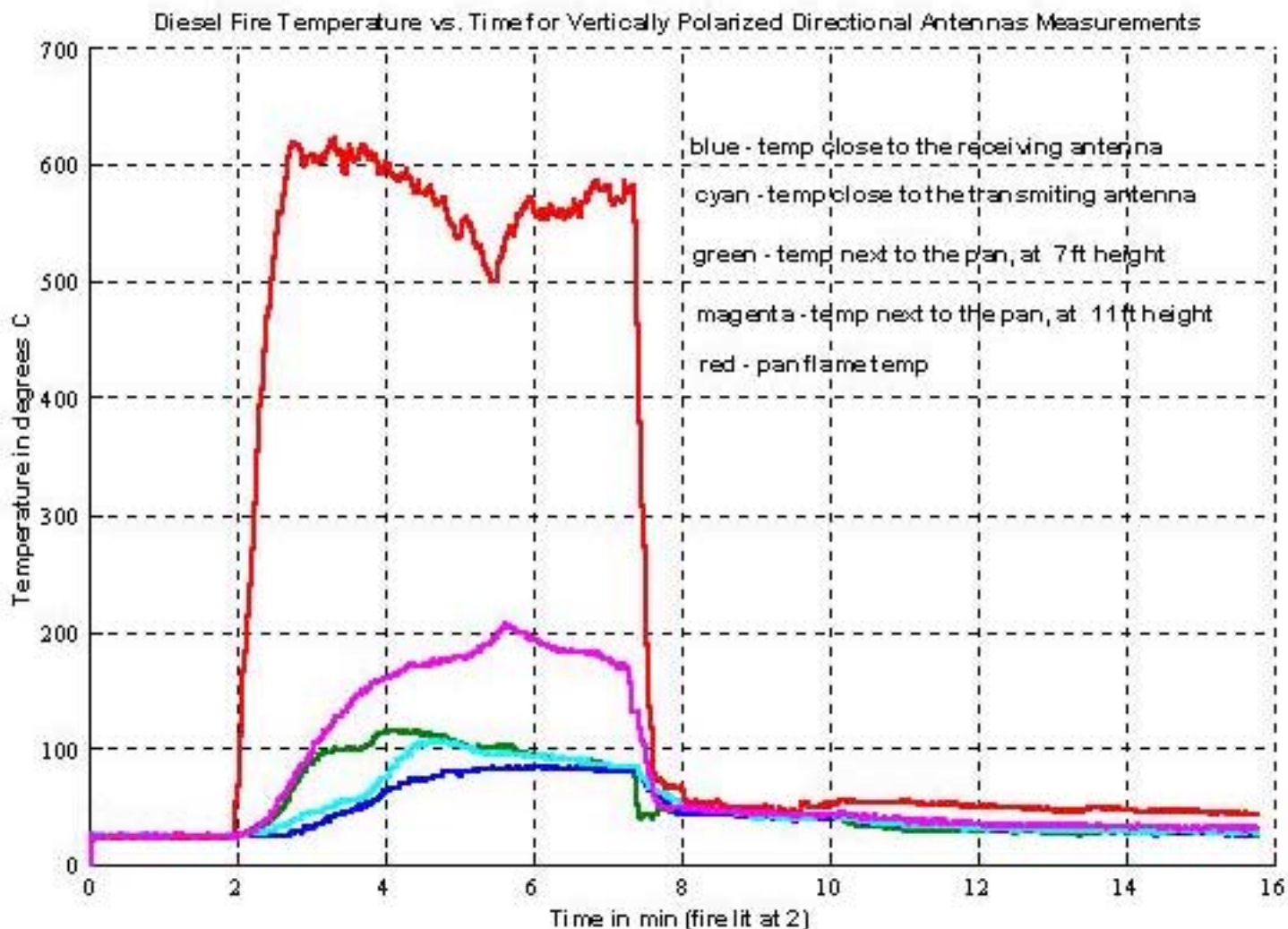


Frequency-Averaged Attenuation for Directional Antennas, V-Pol



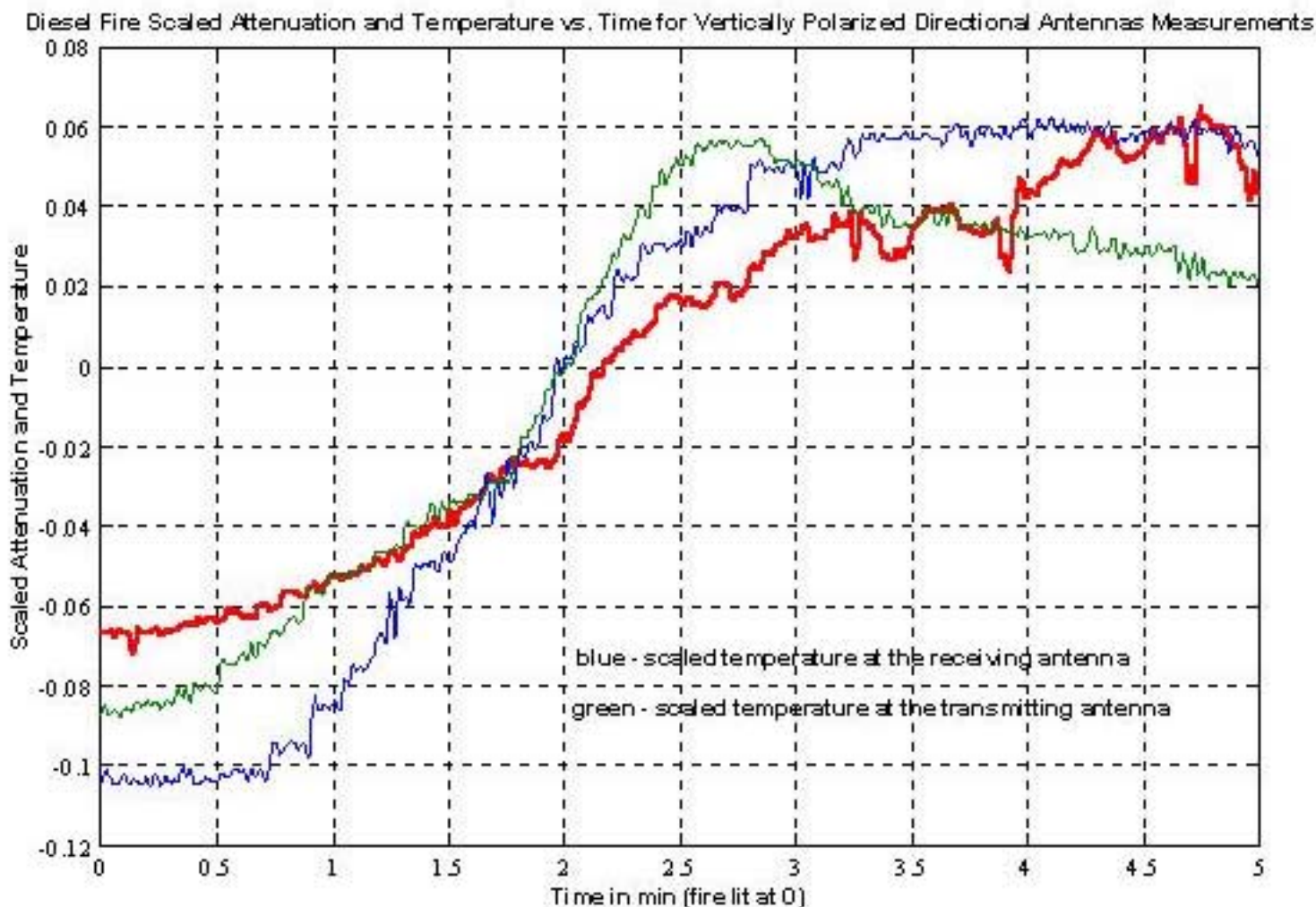


Temperature vs. Time for Directional Antennas, V-Pol



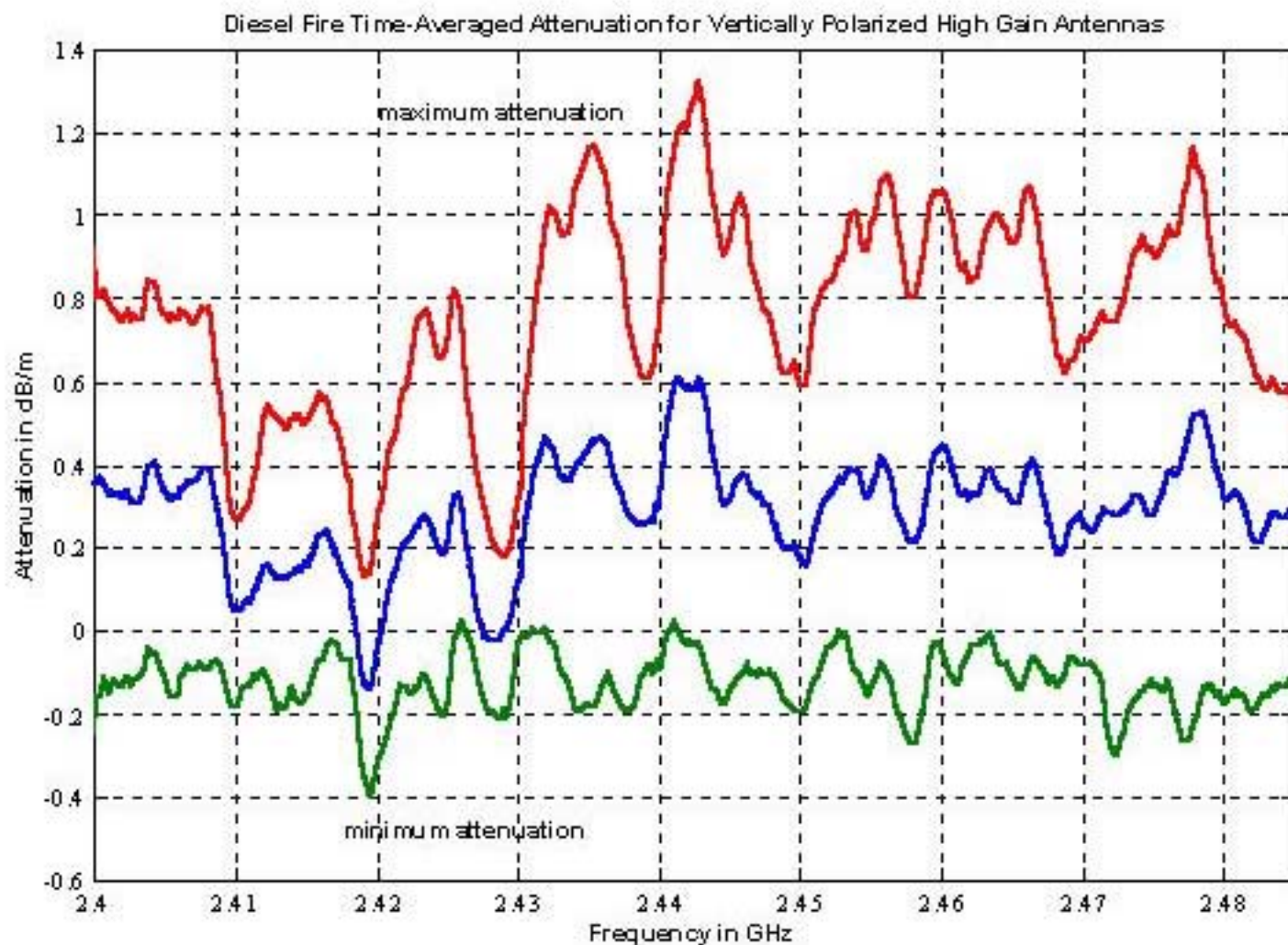


Scaled Attenuation and Temperature vs. Time for Directional Antennas, V-Pol



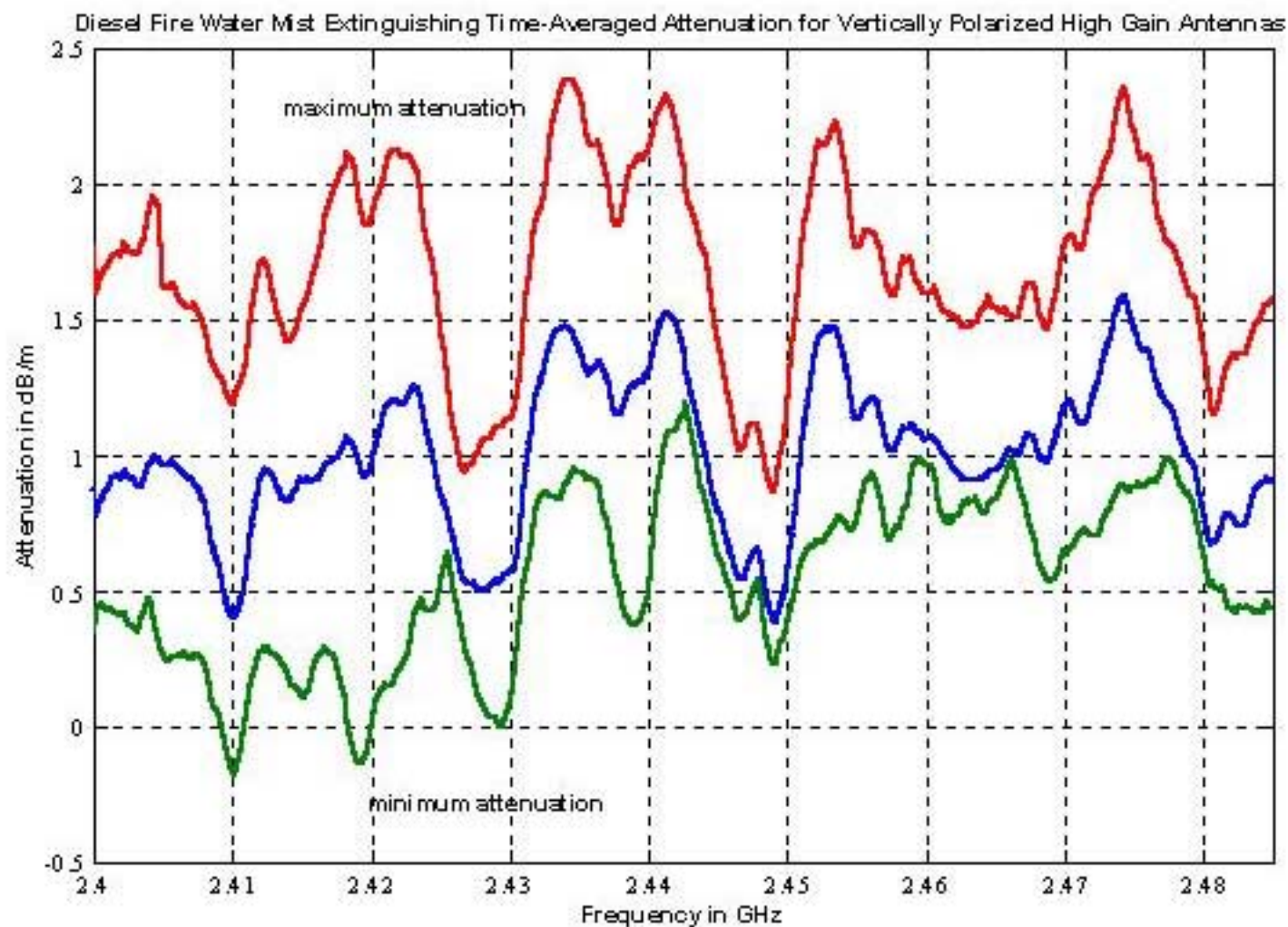


Diesel Fire Attenuation for Directional Antennas, V-Pol



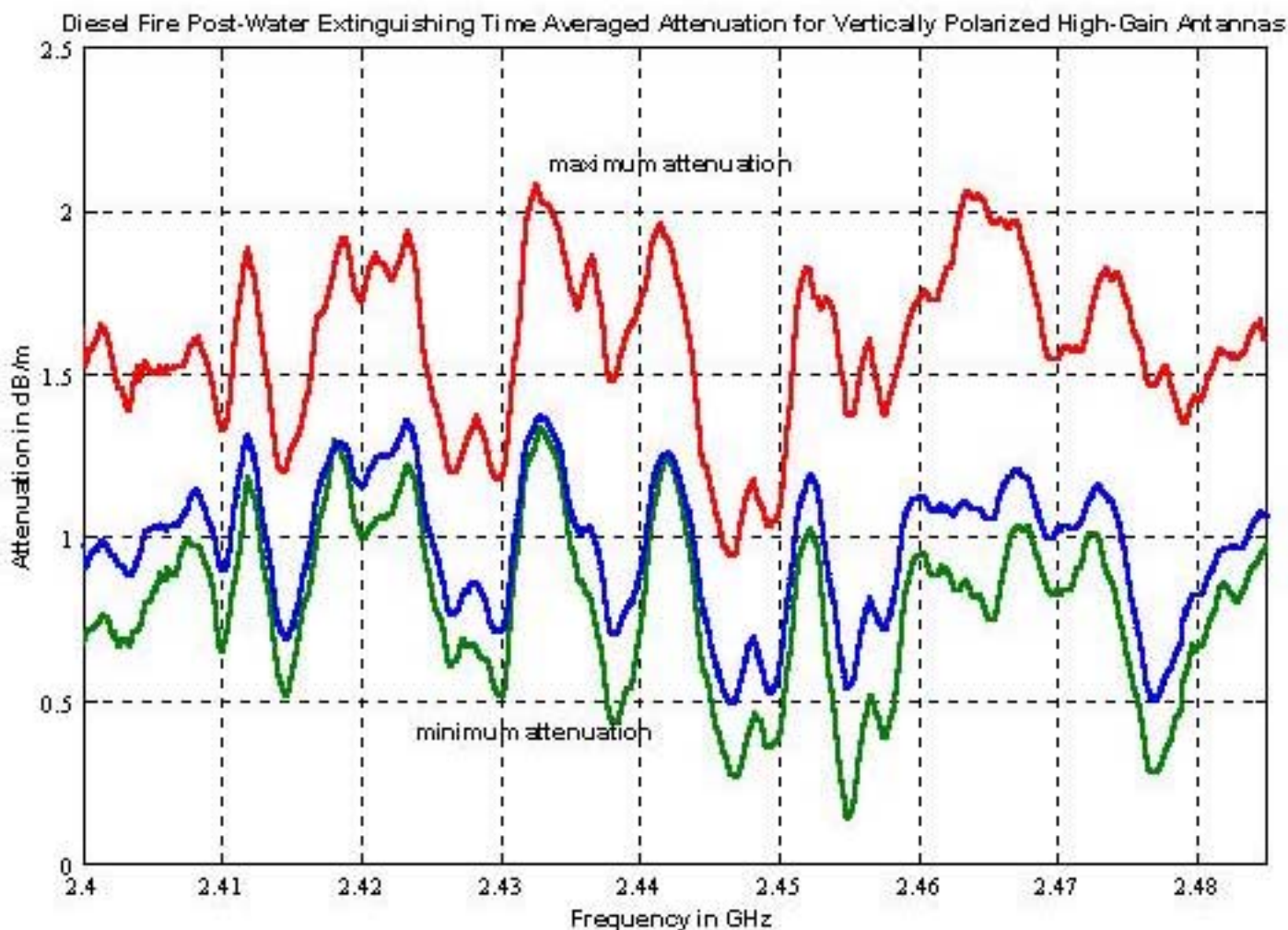


Water Mist Extinguishing Attenuation for Directional Antennas, V-Pol





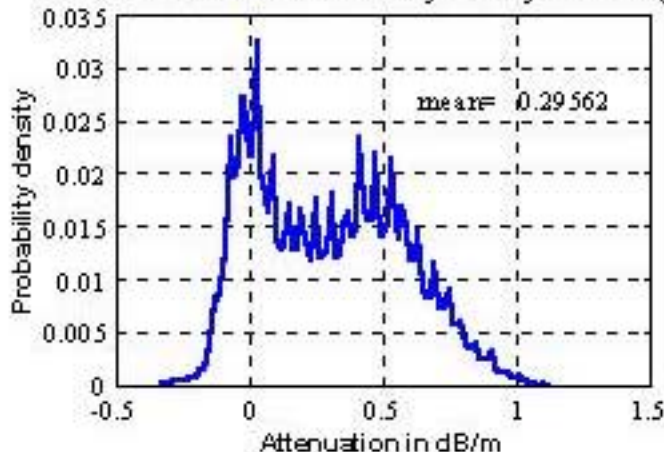
Post-Water Mist Extinguishing Attenuation for Directional Antennas, V-Pol



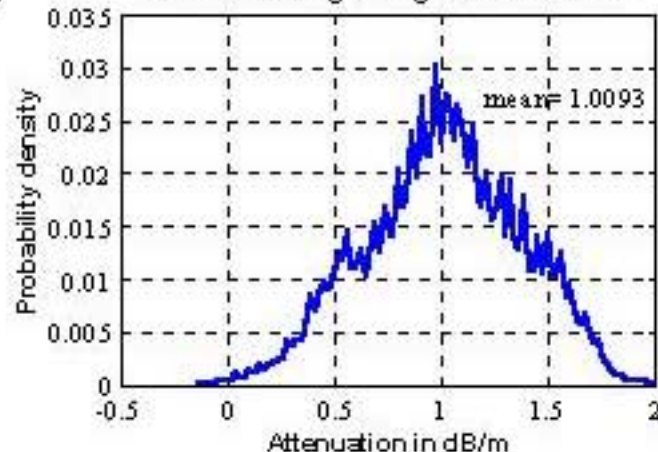


Attenuation Probability Density Functions for Directional Antennas, V-Pol

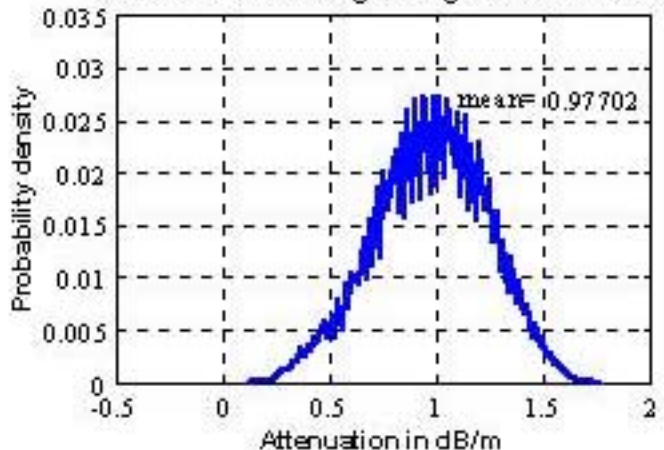
Diesel Fire Attenuation Probability Density Function (PDF)



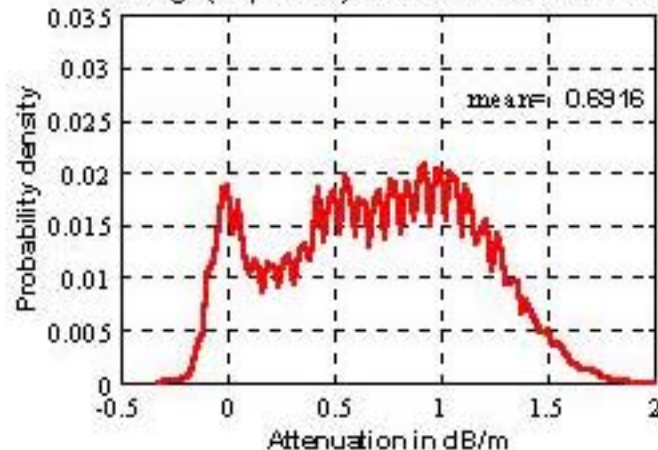
Water Mist Extinguishing Attenuation PDF



Post-Water Mist Extinguishing Attenuation PDF



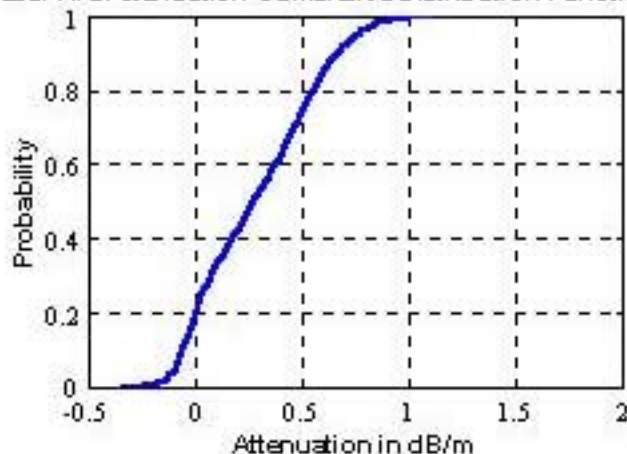
Average (all phases) Attenuation PDF for V-Pol



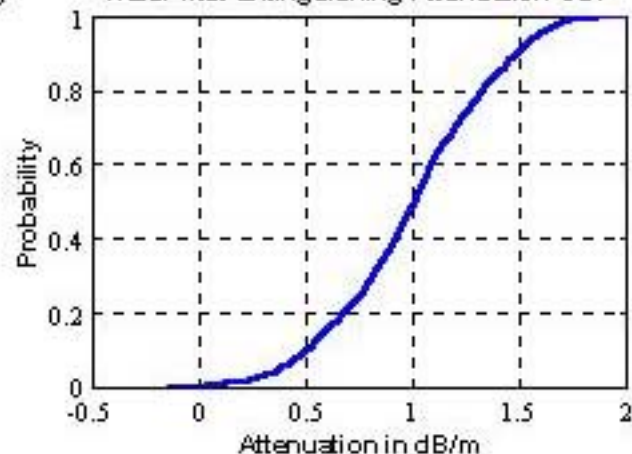


Attenuation Cumulative Distribution Functions for Directional Antennas, V-Pol

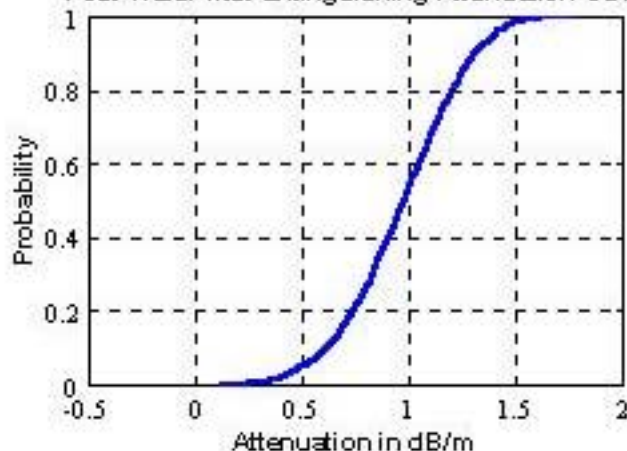
Diesel Fire Attenuation Cumulative Distribution Function (CDF)



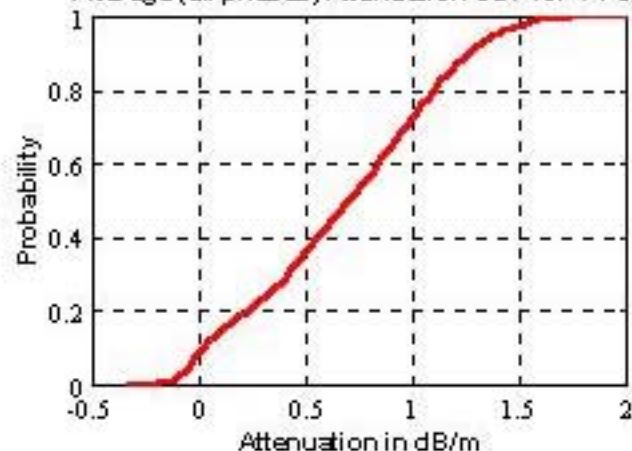
Water Mist Extinguishing Attenuation CDF



Post-Water Mist Extinguishing Attenuation CDF



Average (all phases) Attenuation CDF for V-Pol



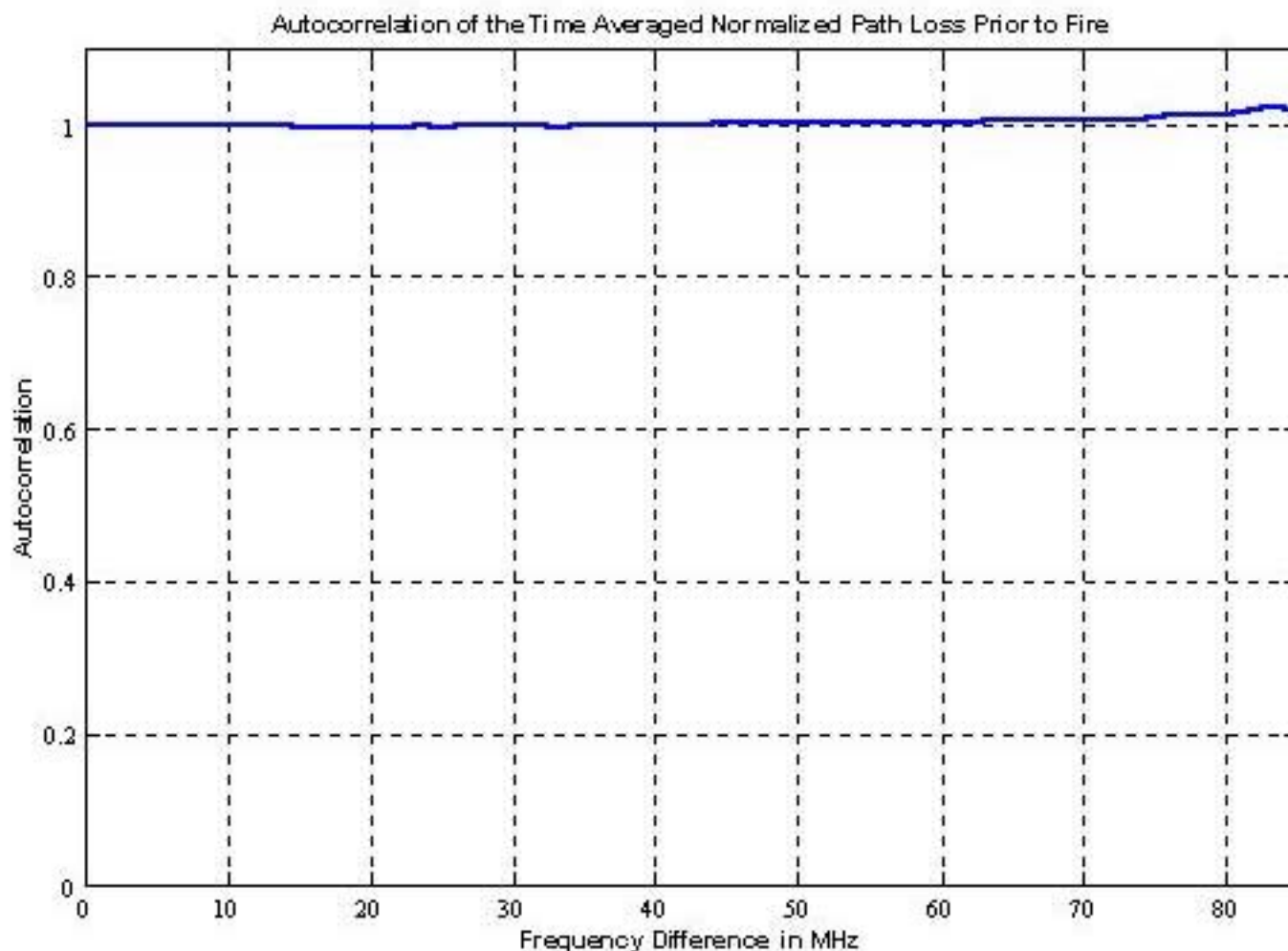


Naval Postgraduate School (NPS) Team

- Ex-USS Shadwell Measurements Team (on site the week of May 10)
 - Dr. Jovan Lebaric
 - LCDR (ret.) Andrew Parker, USN
 - LT Christos Deyannis, Hellenic Navy
 - LT Dimitrios Xifaras, Hellenic Navy
- RF-instrumented van, property of the Special Signals Laboratory of the NPS, was used to transport the measurement equipment from Monterey, CA to Mobile, AL
- Support at NPS
 - Dr. Richard Adler
 - Mr. Robert Vitale, NPS μ W Lab Director

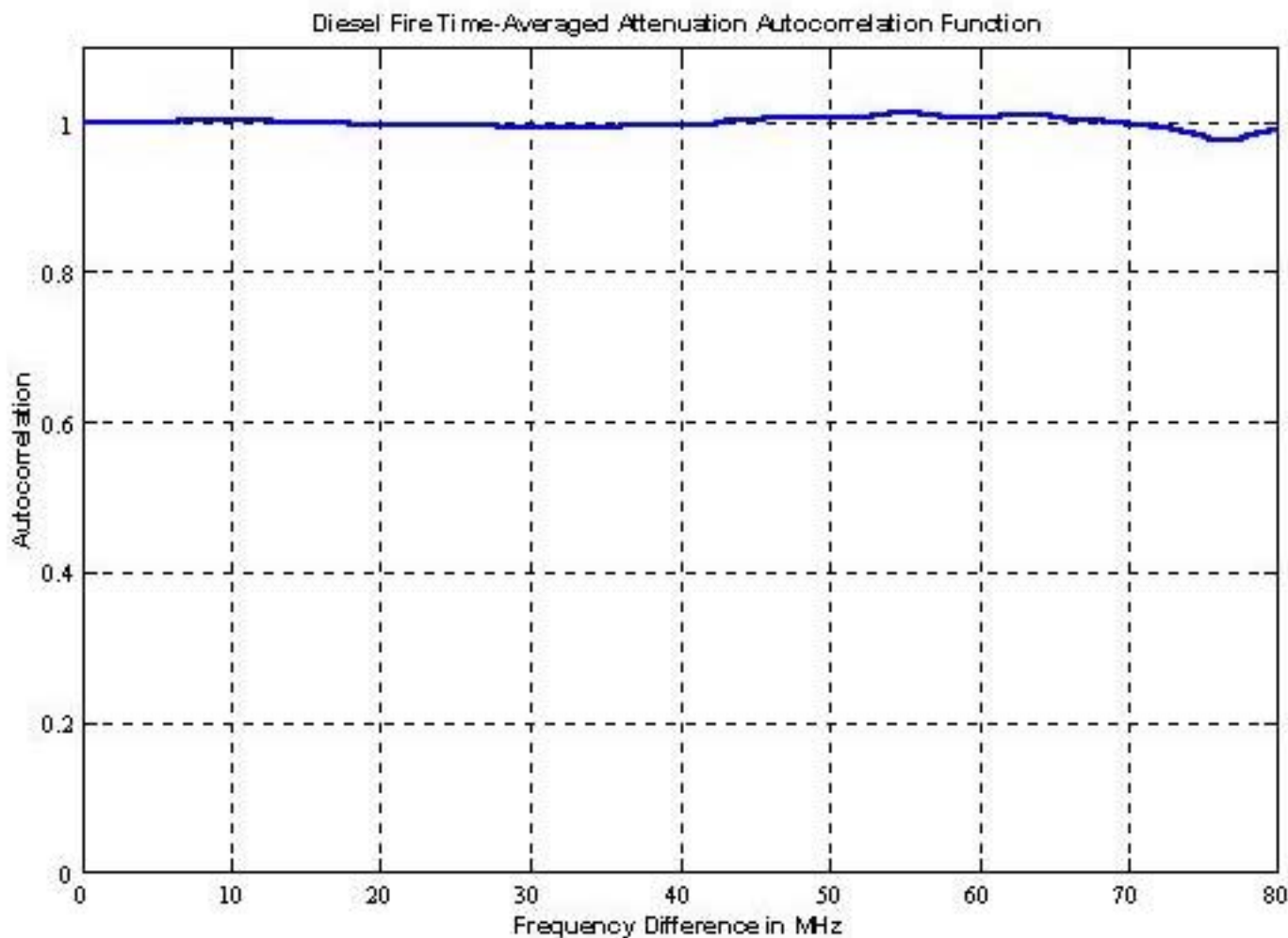


Normalized Autocorrelation Function for Directional Antennas Prior to Fire, V-Pol



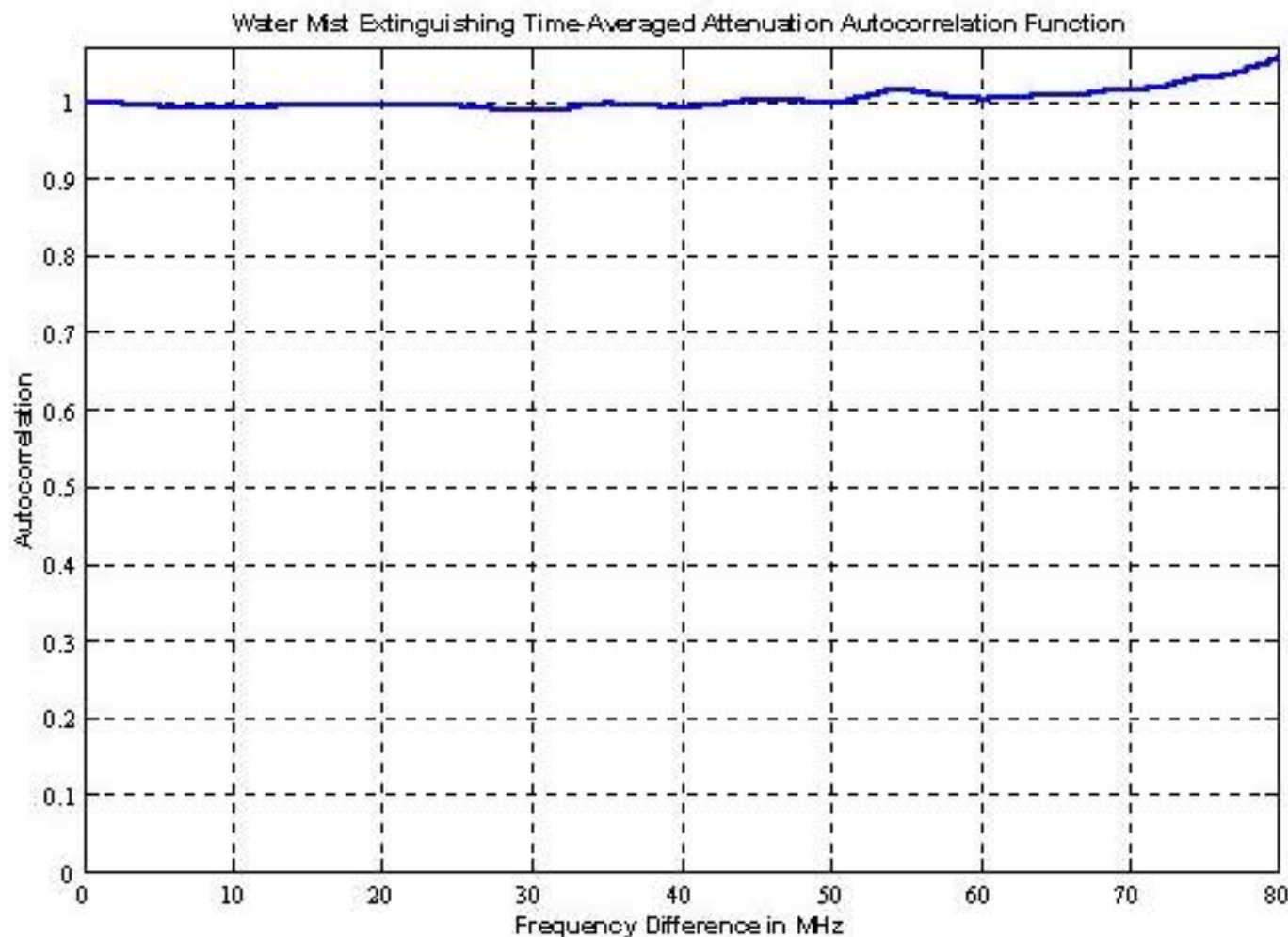


Diesel Fire Normalized Autocorrelation Function for Directional Antennas, V-Pol



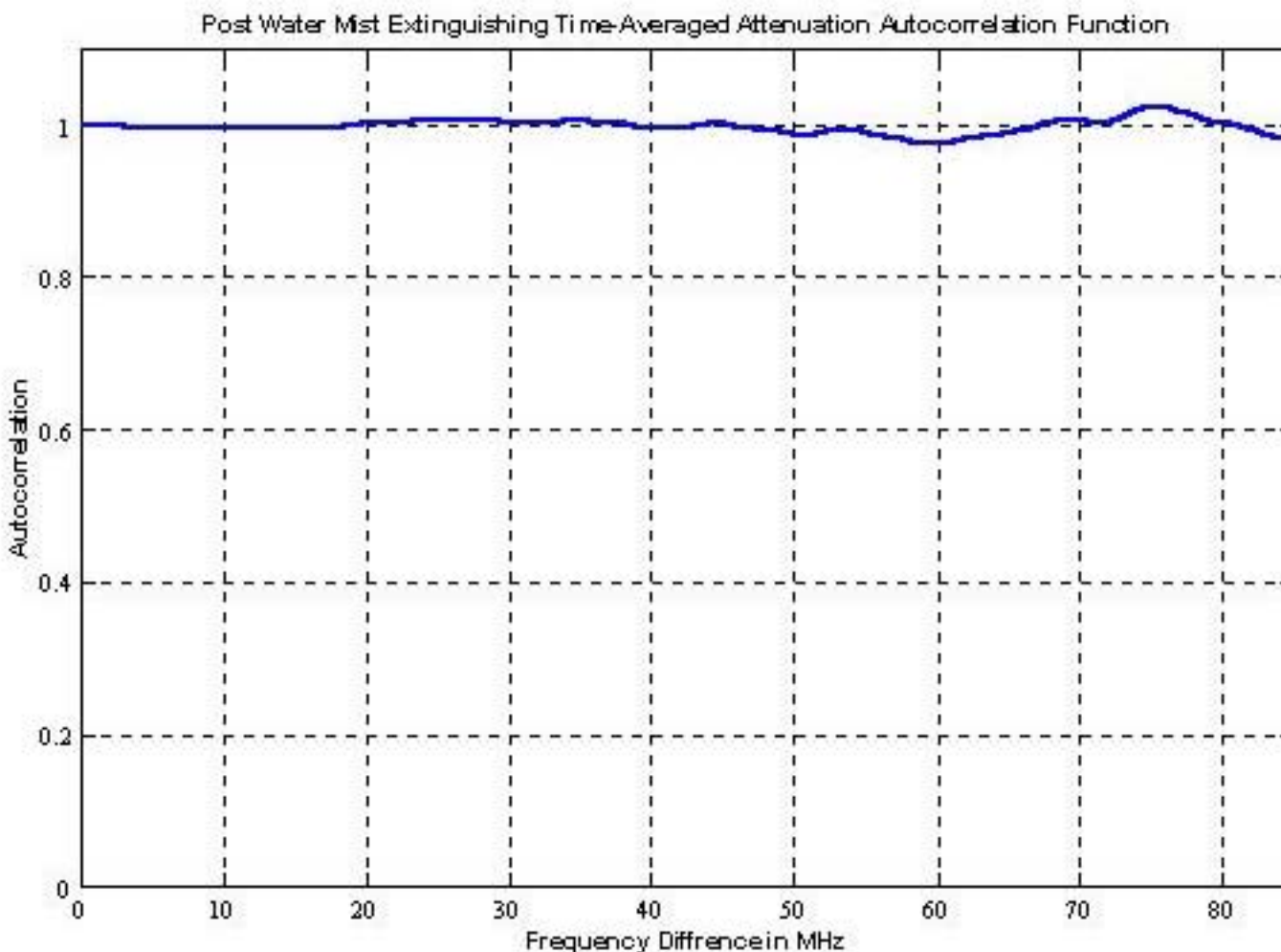


Water Mist Extinguishing Normalized Autocorrelation Function for Directional Antennas, V-Pol





Post-Water Mist Extinguishing Normalized Autocorrelation Function for Directional Antennas, V-Pol



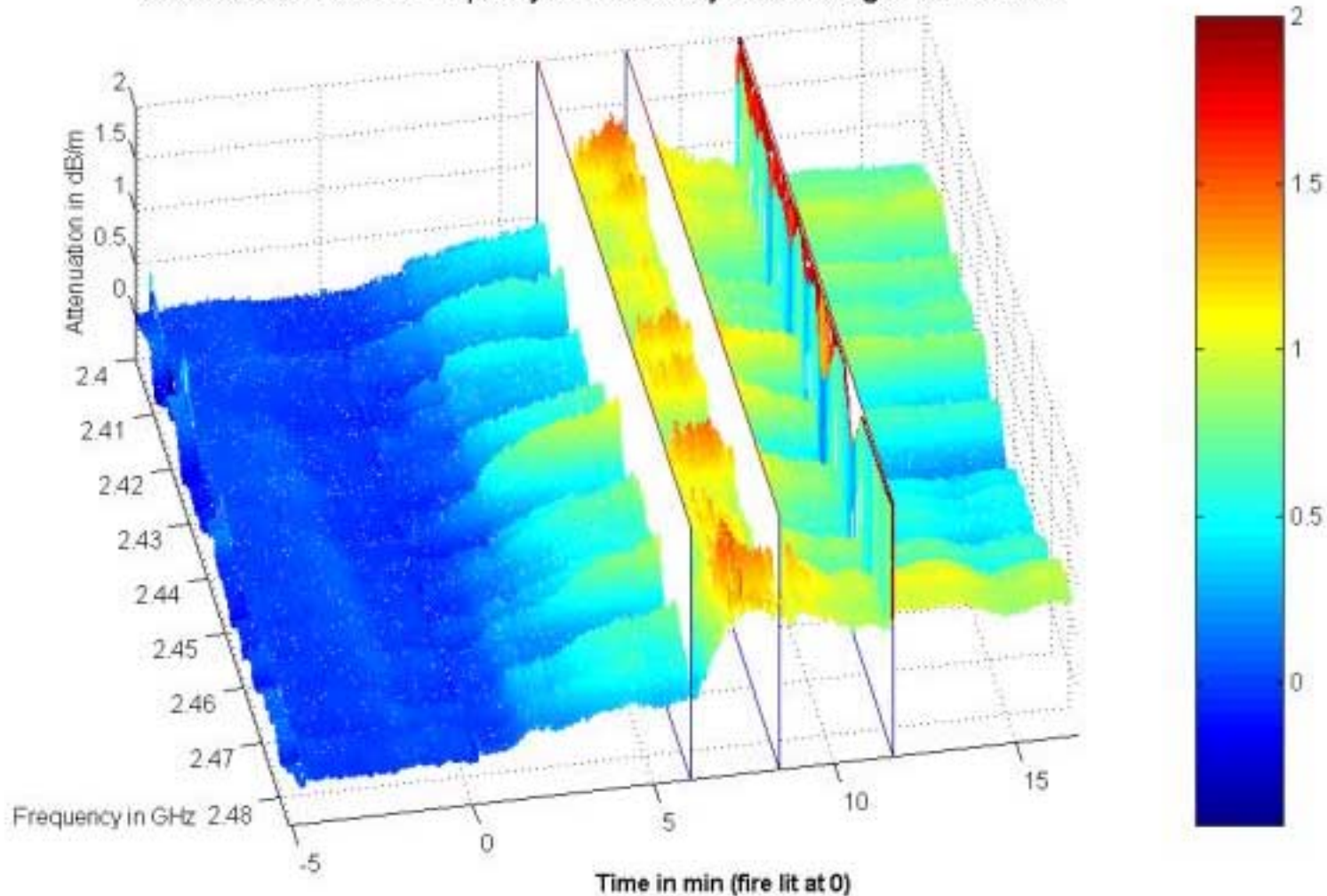


Results for Horizontally Polarized Directional (High Gain) Antennas



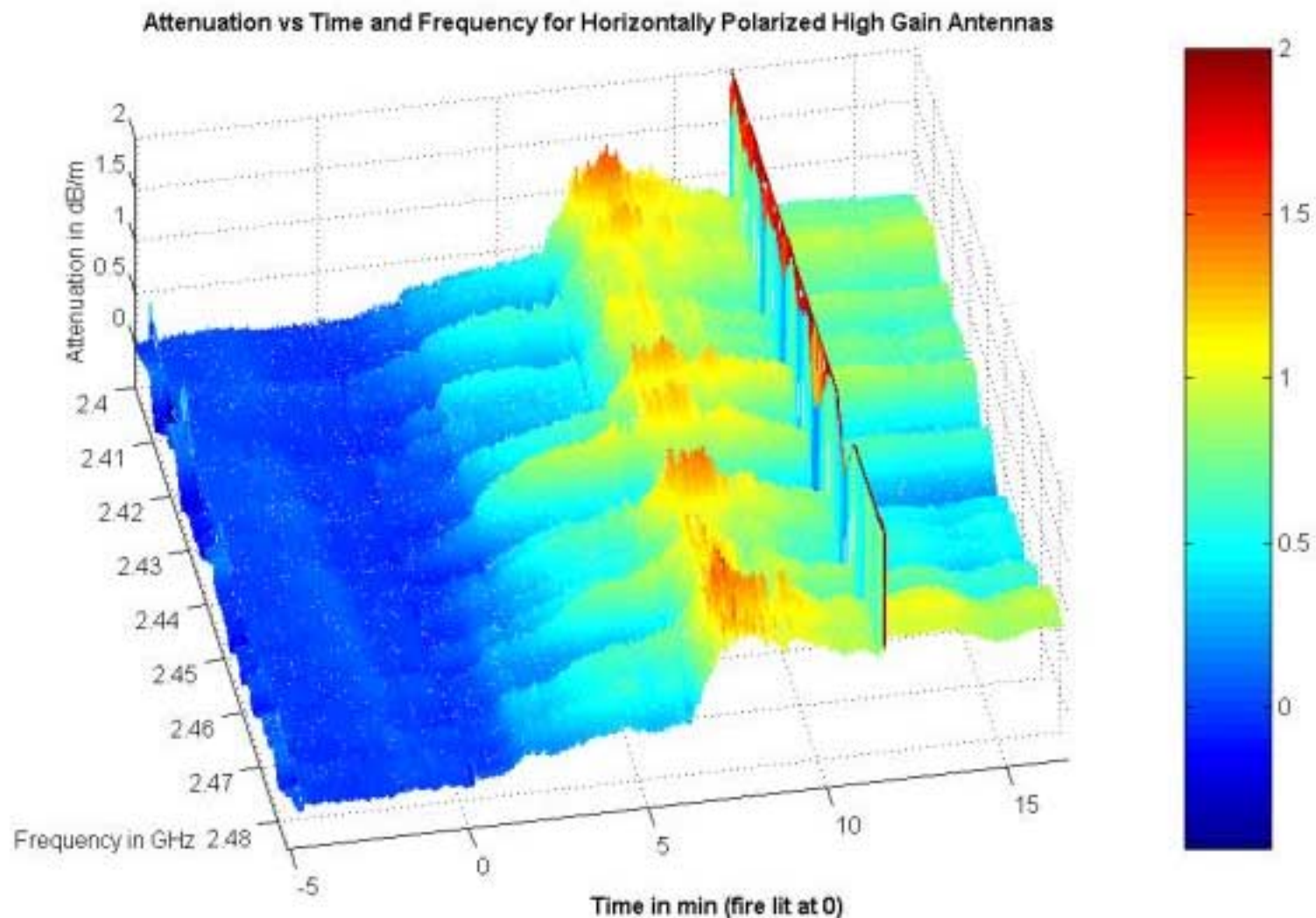
Attenuation for Directional Antennas, H-Pol

Attenuation vs Time and Frequency for Horizontally Polarized High Gain Antennas



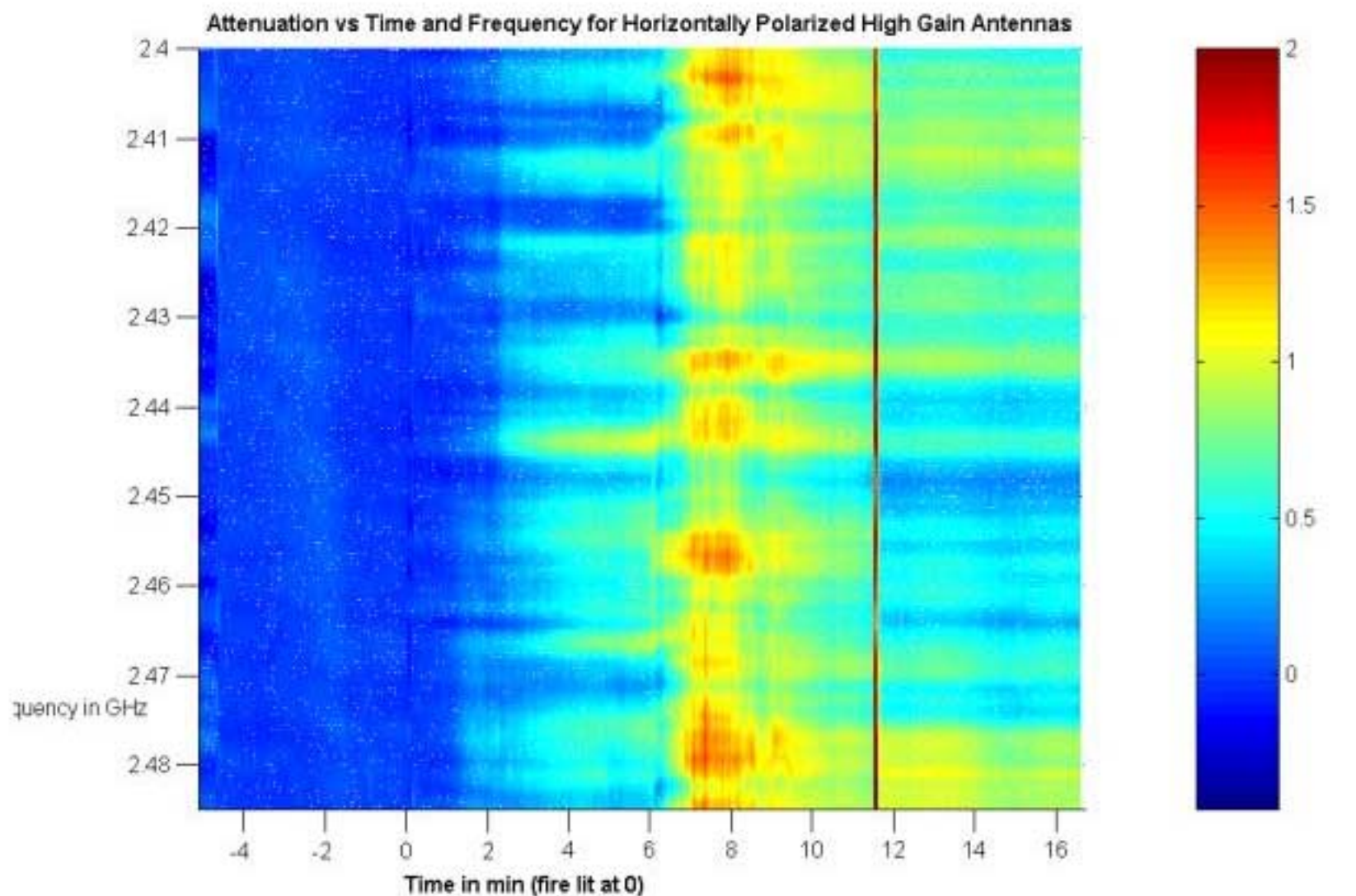


Attenuation for Directional Antennas, H-Pol



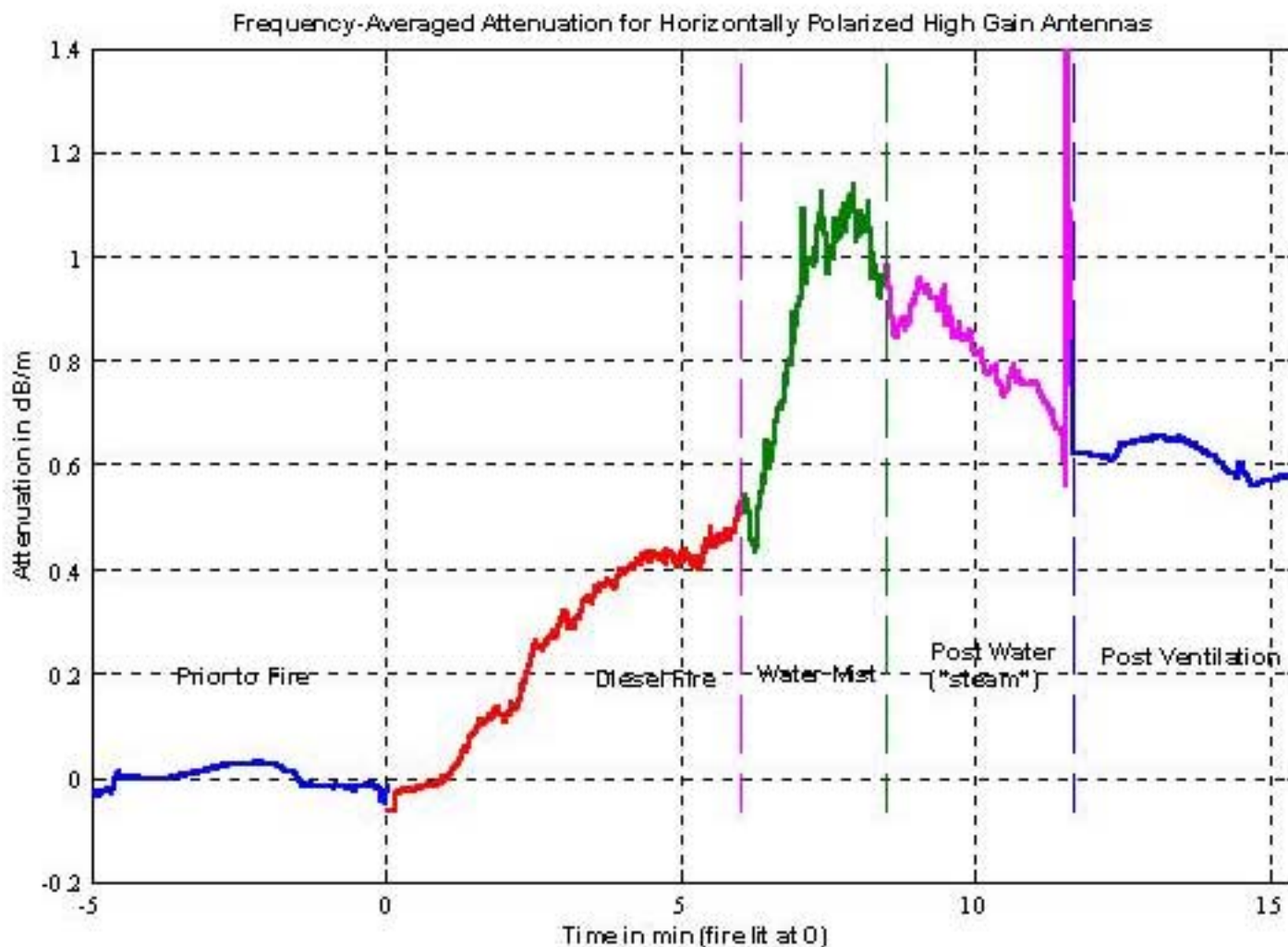


Attenuation for Directional Antennas, H-Pol



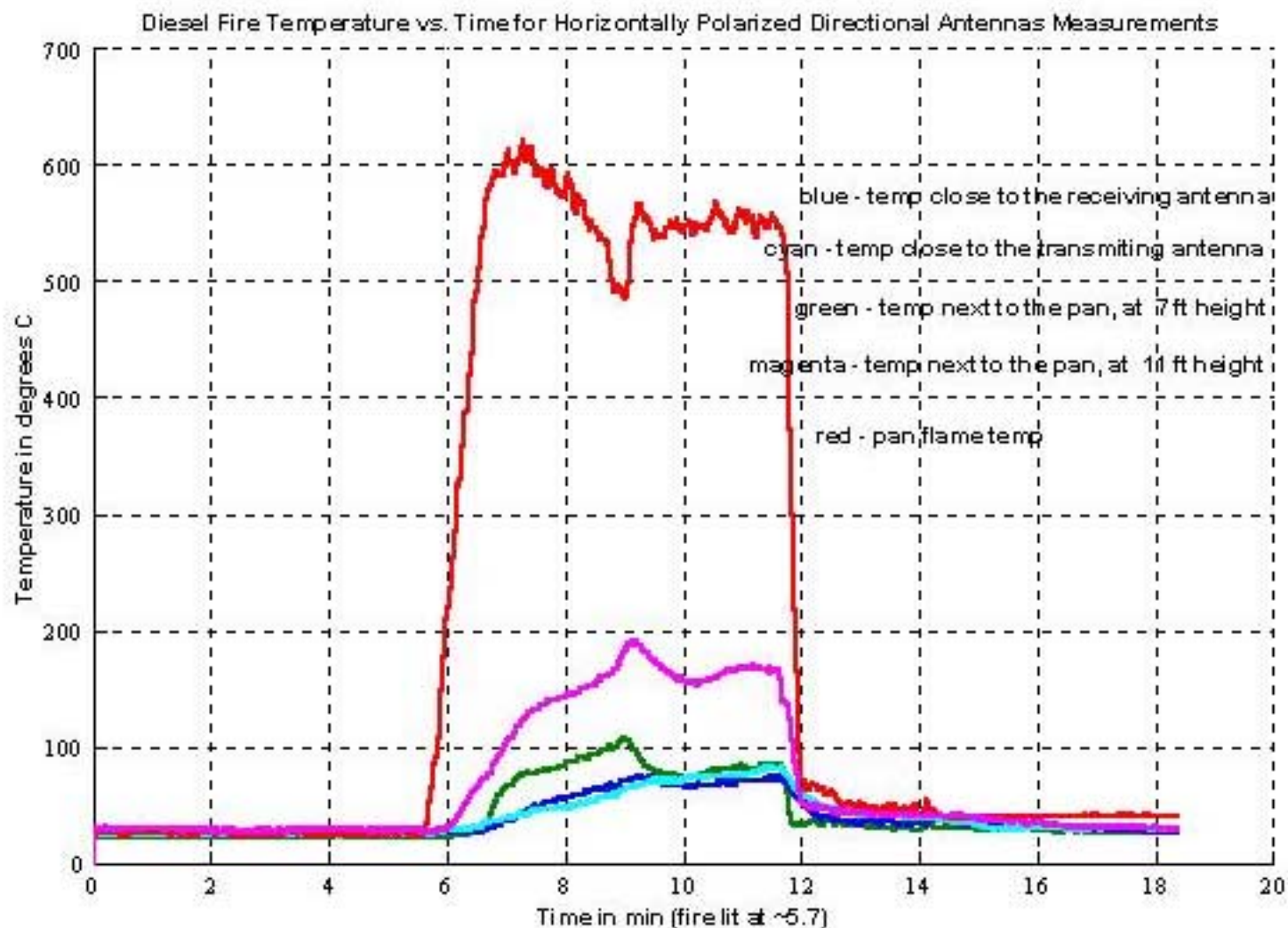


Frequency-Averaged Attenuation for Directional Antennas, H-Pol





Temperature vs. Time for Directional Antennas, H-Pol





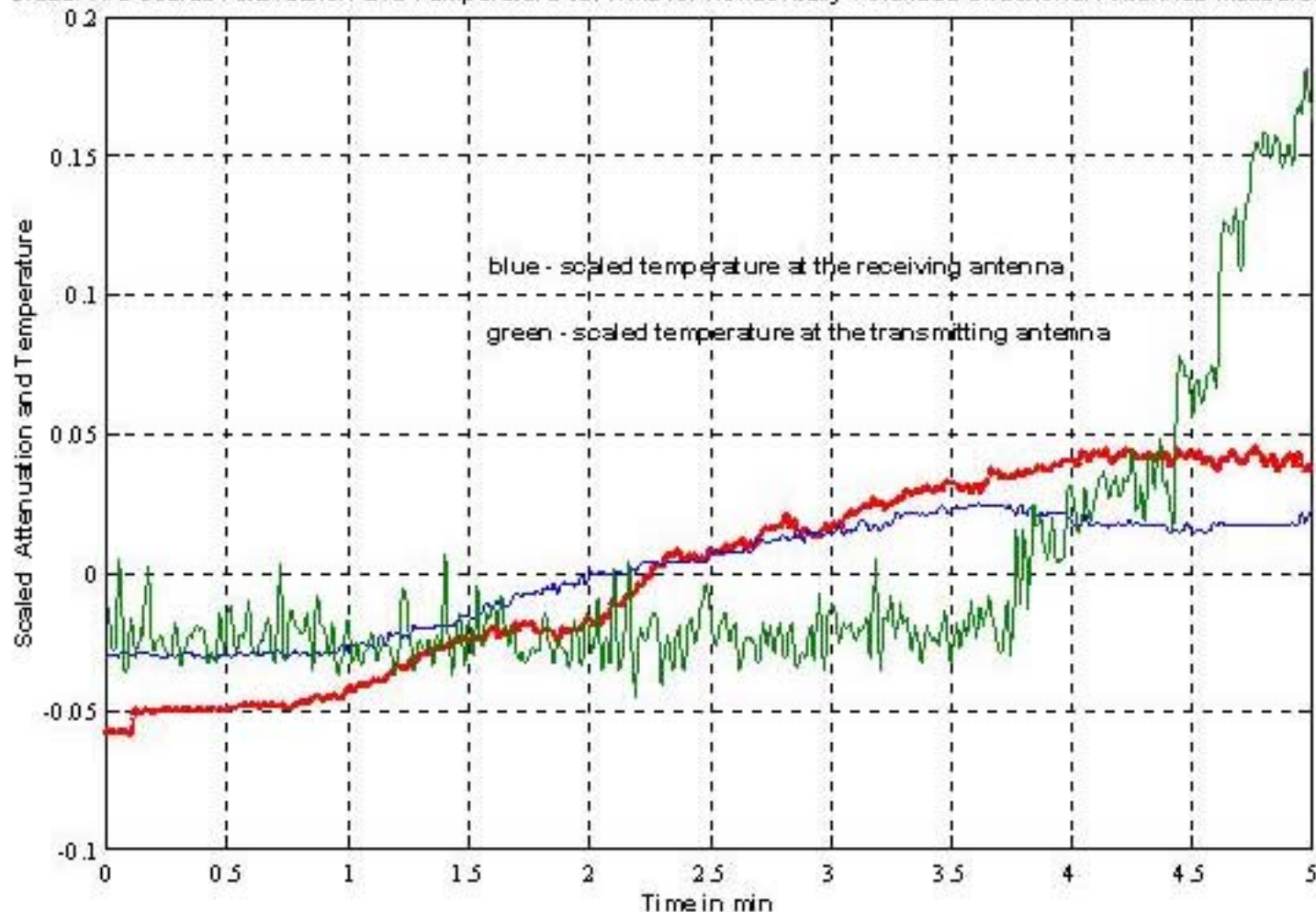
Measurements Summary

- RF Attenuation in the ISM band was measured using a pair of narrowband, narrow beam (high gain/directivity) linearly polarized antennas
- The effects of fire and water mist fire-extinguishing system were also measured using a pair of non-directional patch antennas which are more representative of typical communications antennas for indoor use



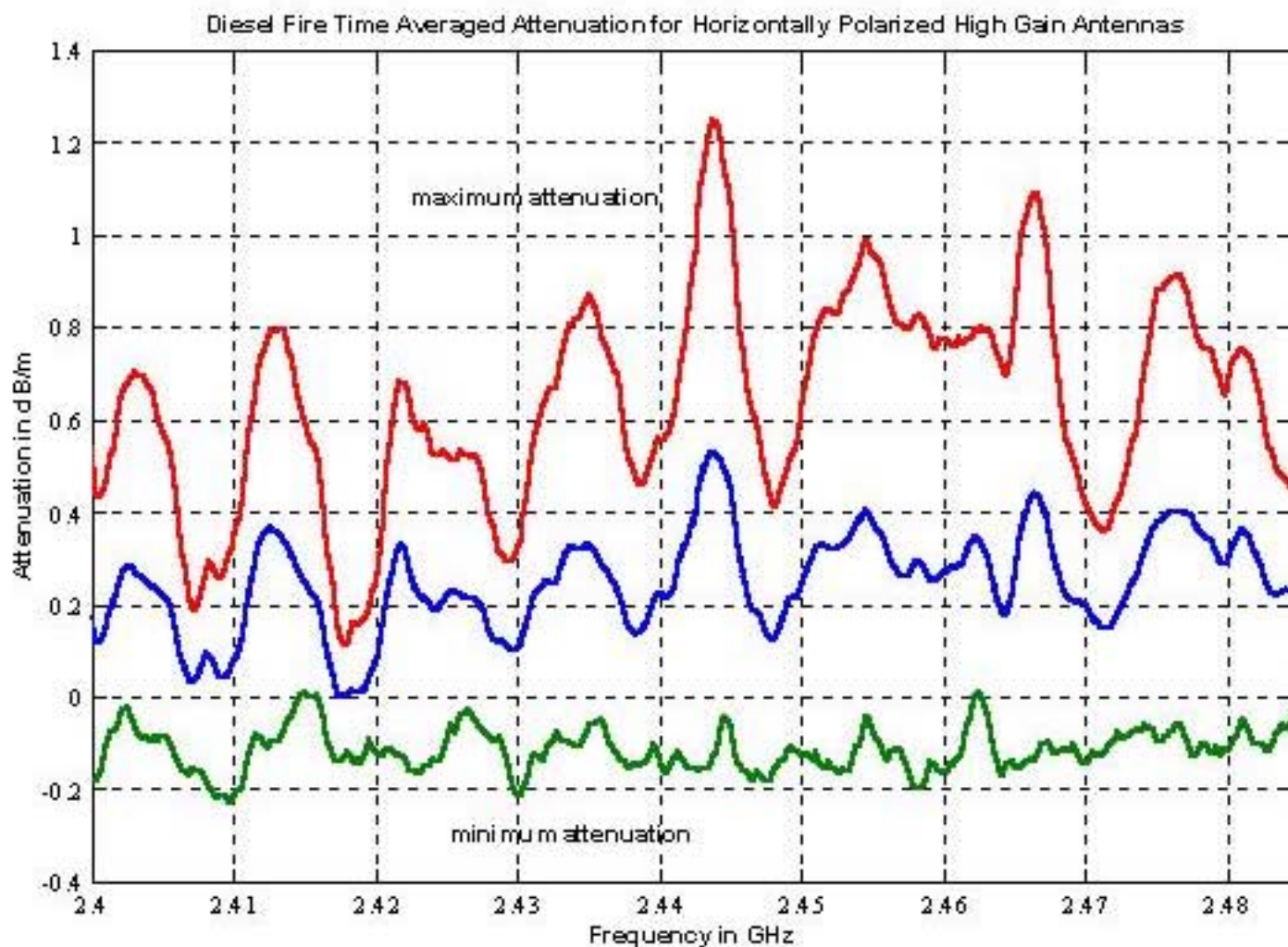
Scaled Attenuation and Temperature vs. Time for Directional Antennas, H-Pol

Diesel Fire Scaled Attenuation and Temperature vs. Time for Horizontally Polarized Directional Antennas Measurements





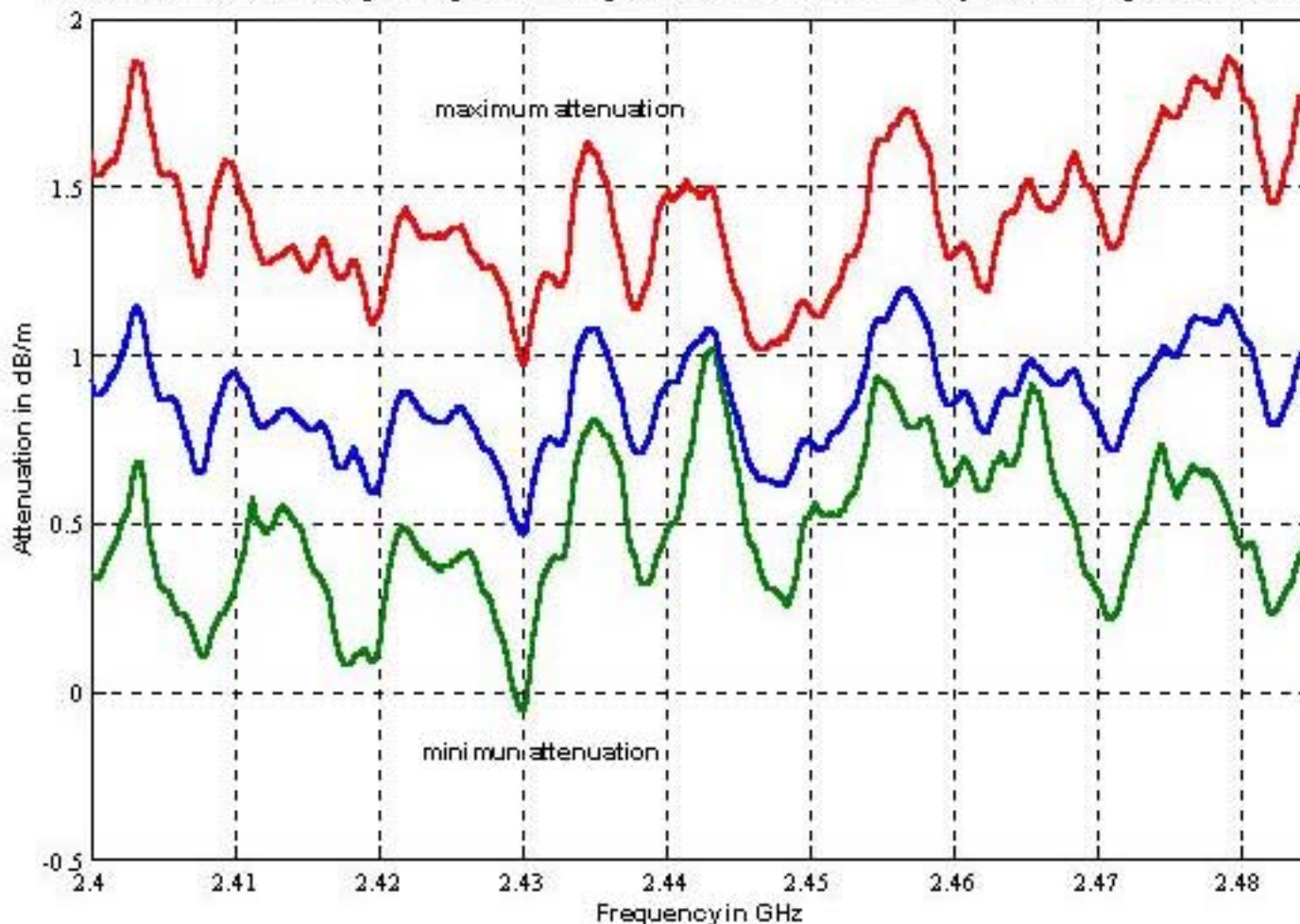
Diesel Fire Attenuation for Directional Antennas, H-Pol





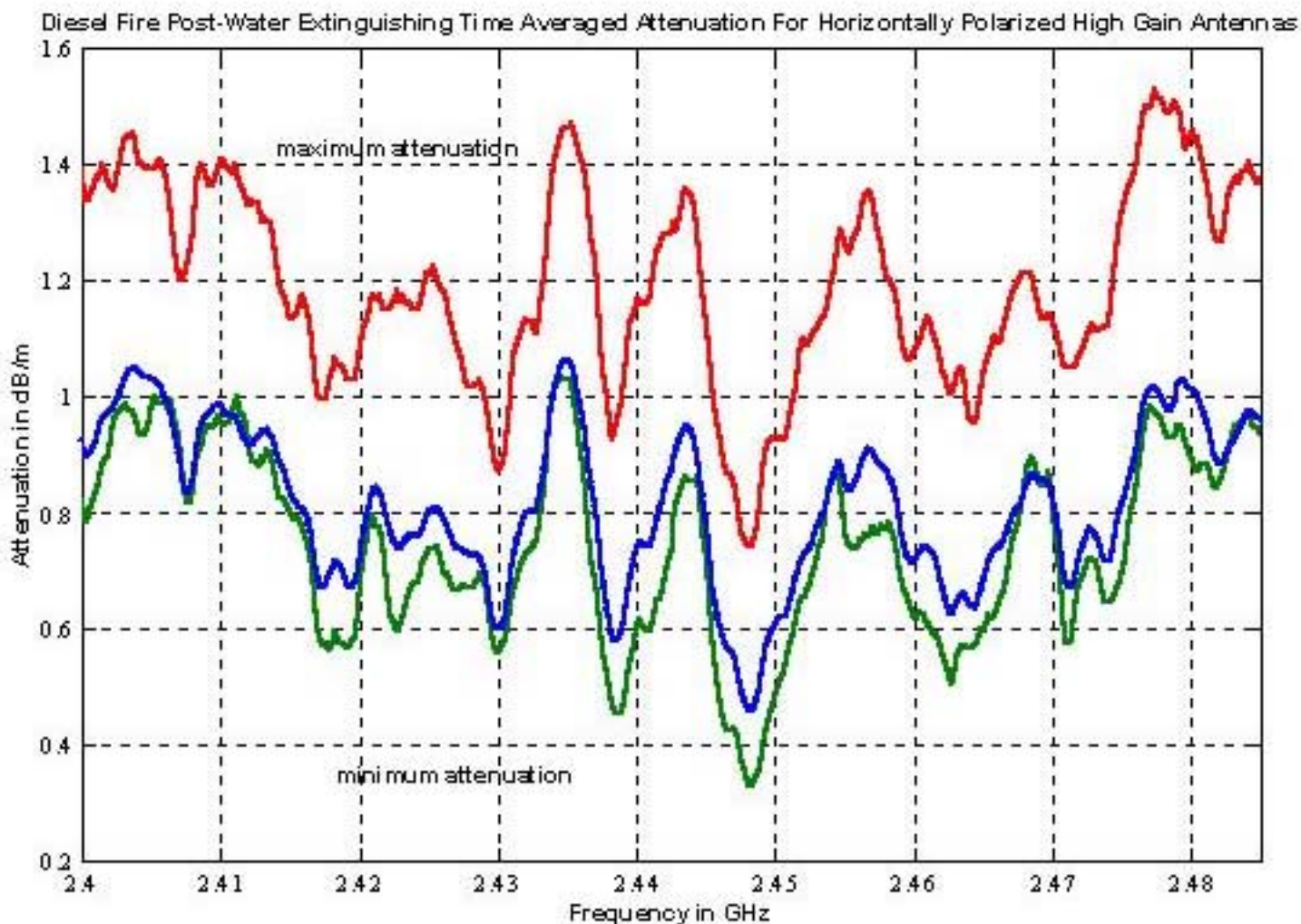
Water Mist Extinguishing Attenuation for Directional Antennas, H-Pol

Diesel Fire Water Mist Extinguishing Time-Averaged Attenuation for Horizontally Polarized High Gain Antennas





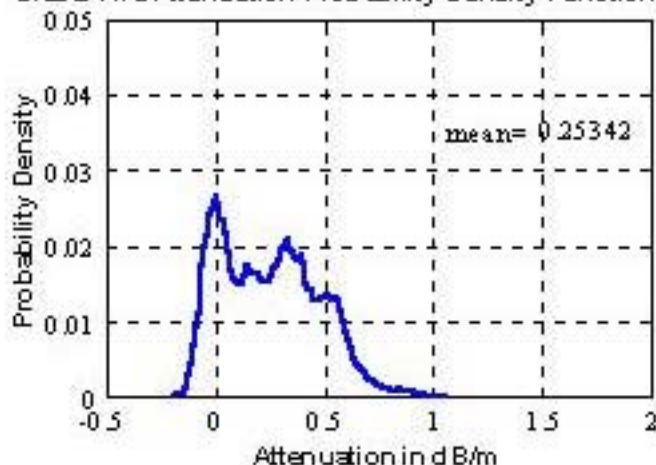
Post-Water Mist Extinguishing Attenuation for Directional Antennas, H-Pol



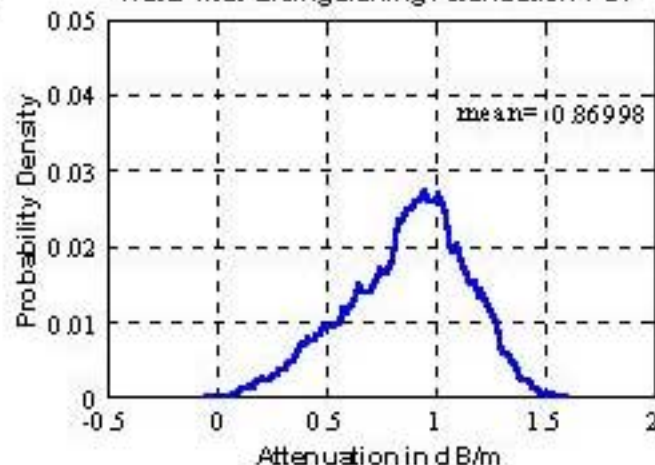


Attenuation Probability Density Functions for Directional Antennas, H-Pol

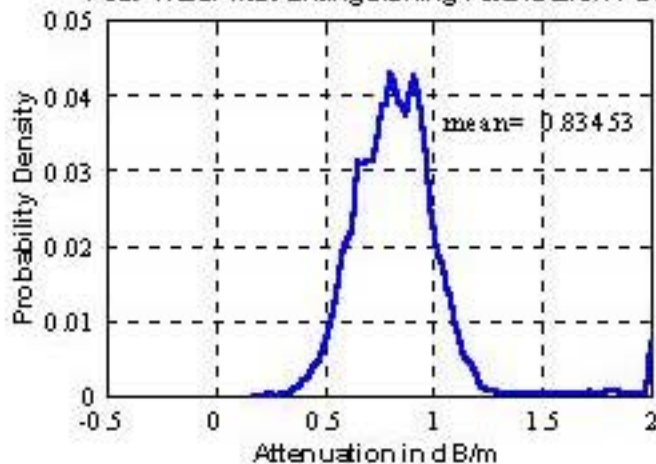
Diesel Fire Attenuation Probability Density Function (PDF)



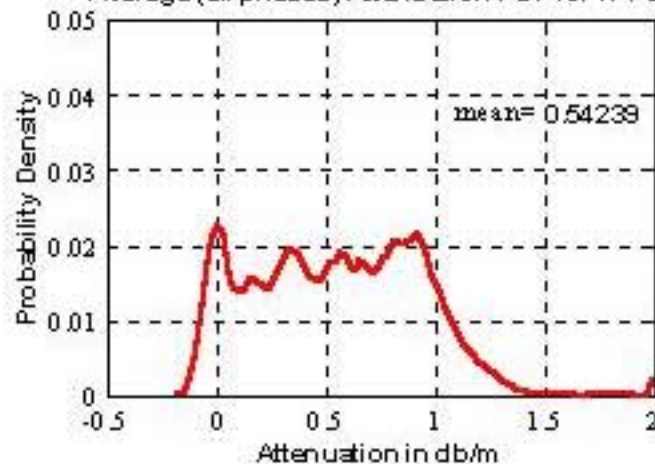
Water Mist Extinguishing Attenuation PDF



Post-Water Mist Extinguishing Attenuation PDF



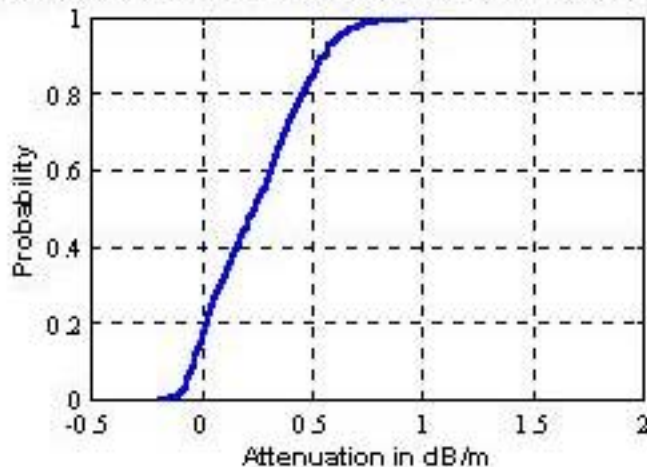
Average (all phases) Attenuation PDF for H-Pol



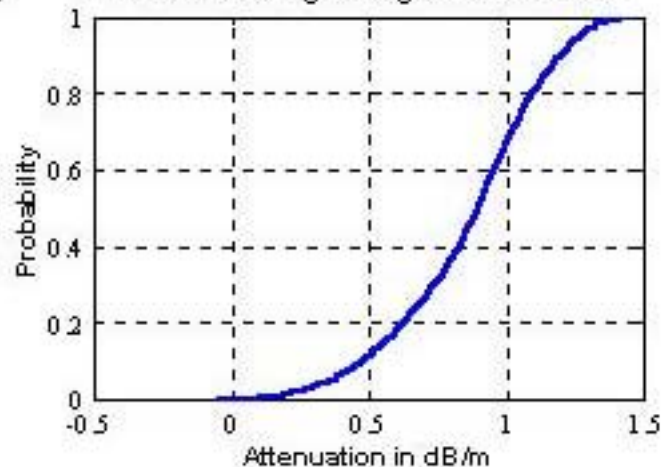


Attenuation Cumulative Distribution Functions for Directional Antennas, H-Pol

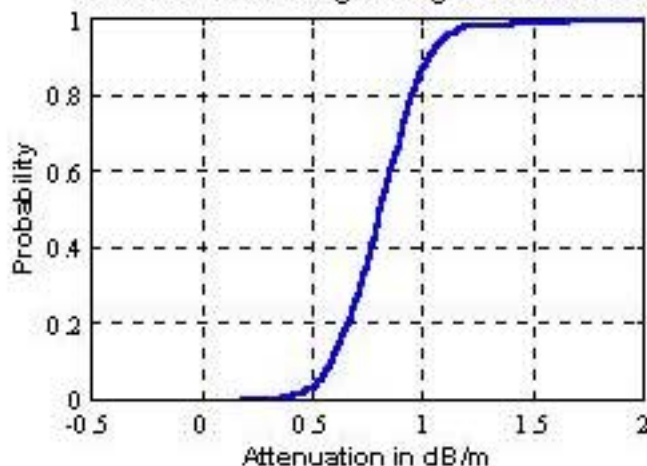
Diesel Fire Attenuation Cumulative Distribution Function (CDF)



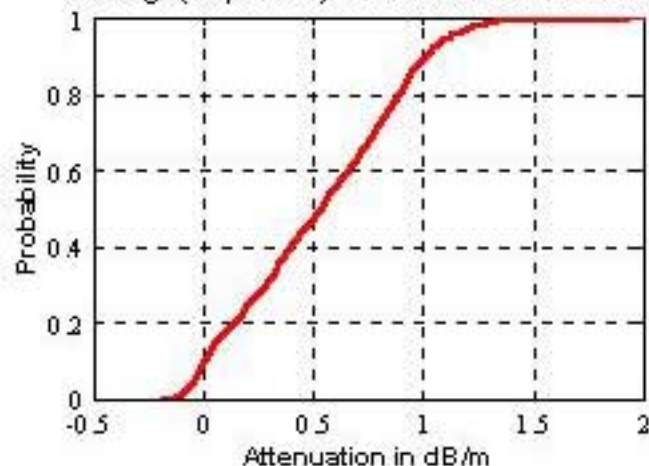
Water Mist Extinguishing Attenuation CDF



Post-Water Mist Extinguishing Attenuation CDF

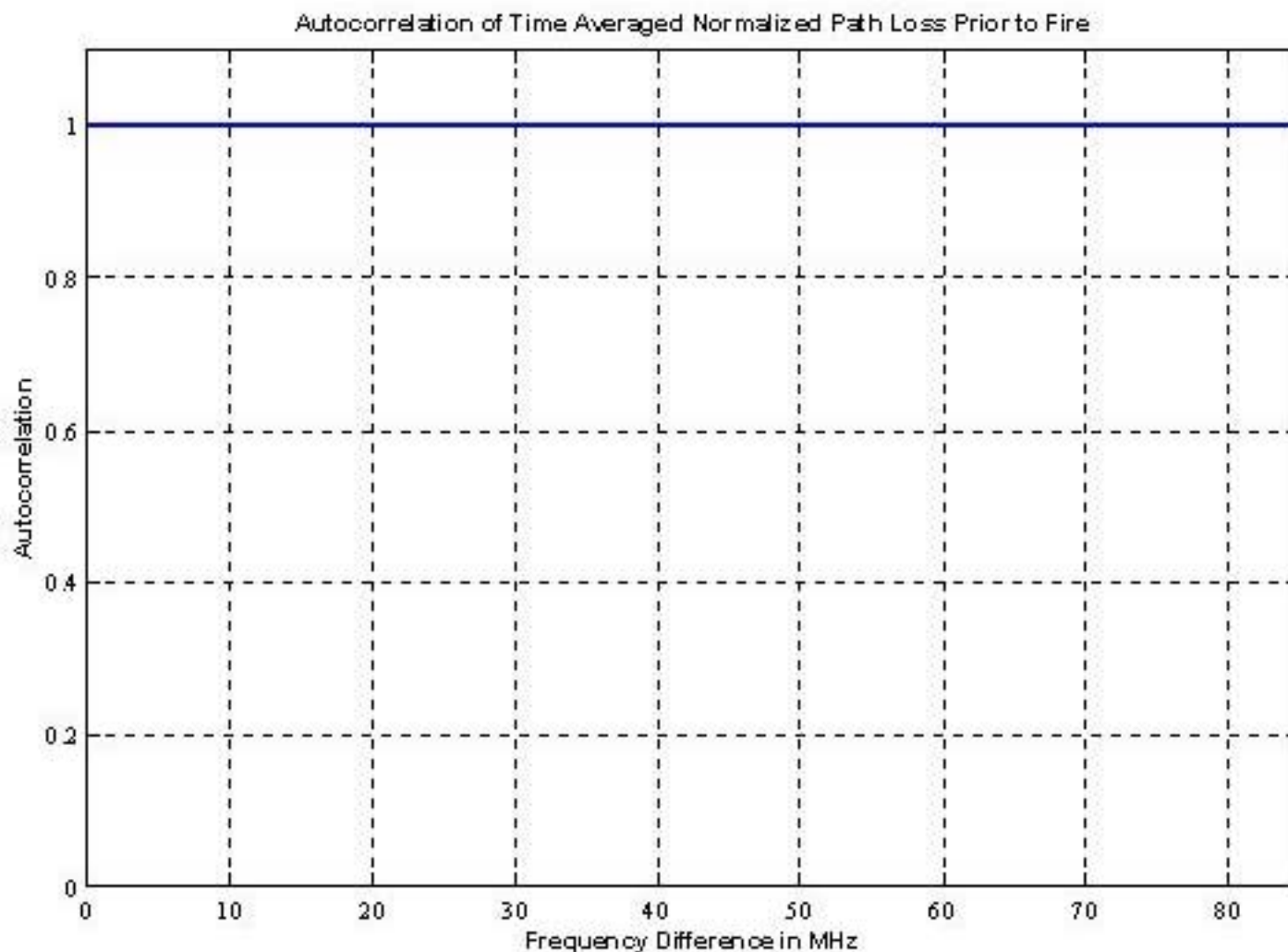


Average (all phases) Attenuation CDF for H-Pol



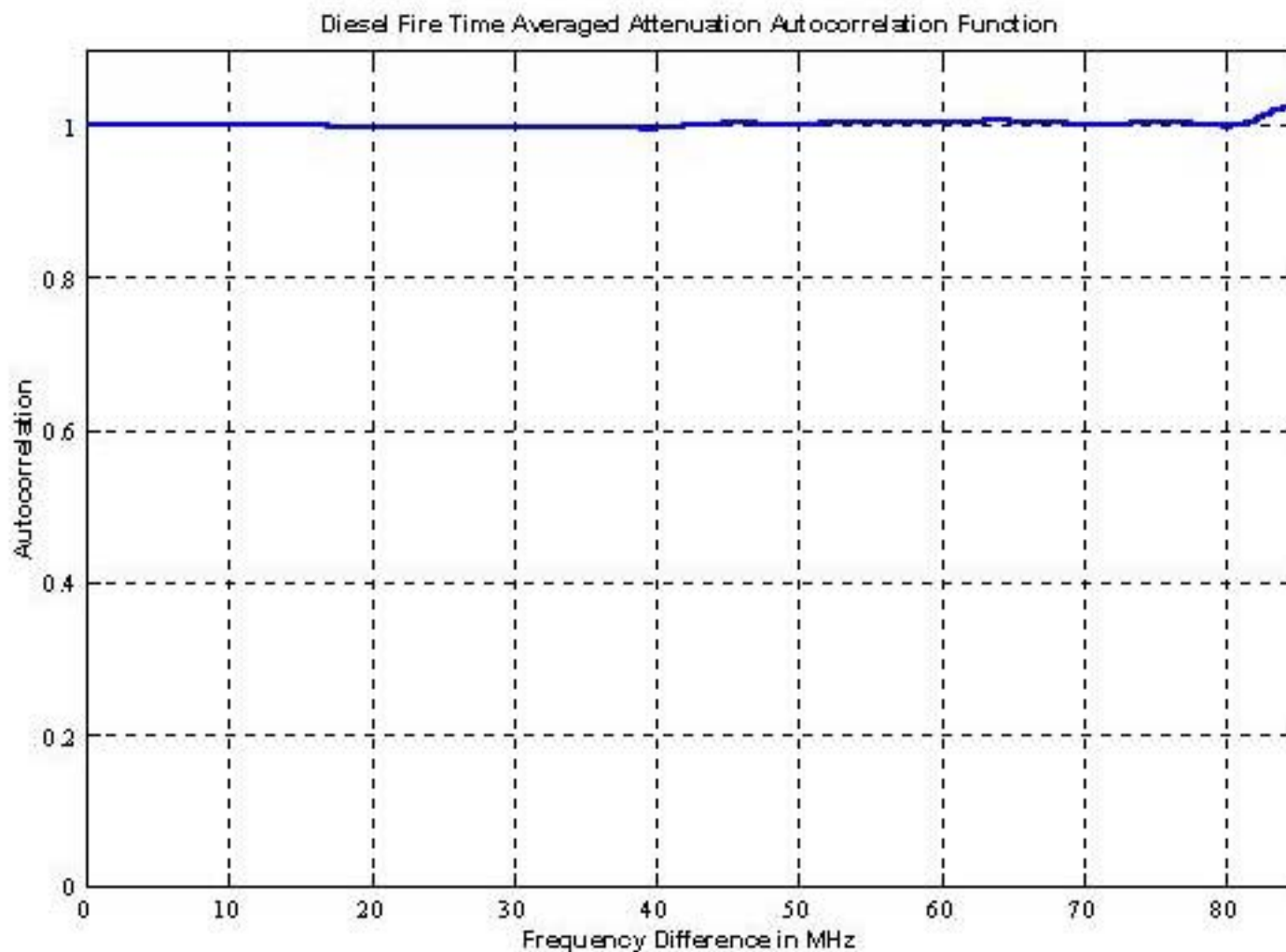


Normalized Autocorrelation Function for Directional Antennas Prior to Fire, H-Pol



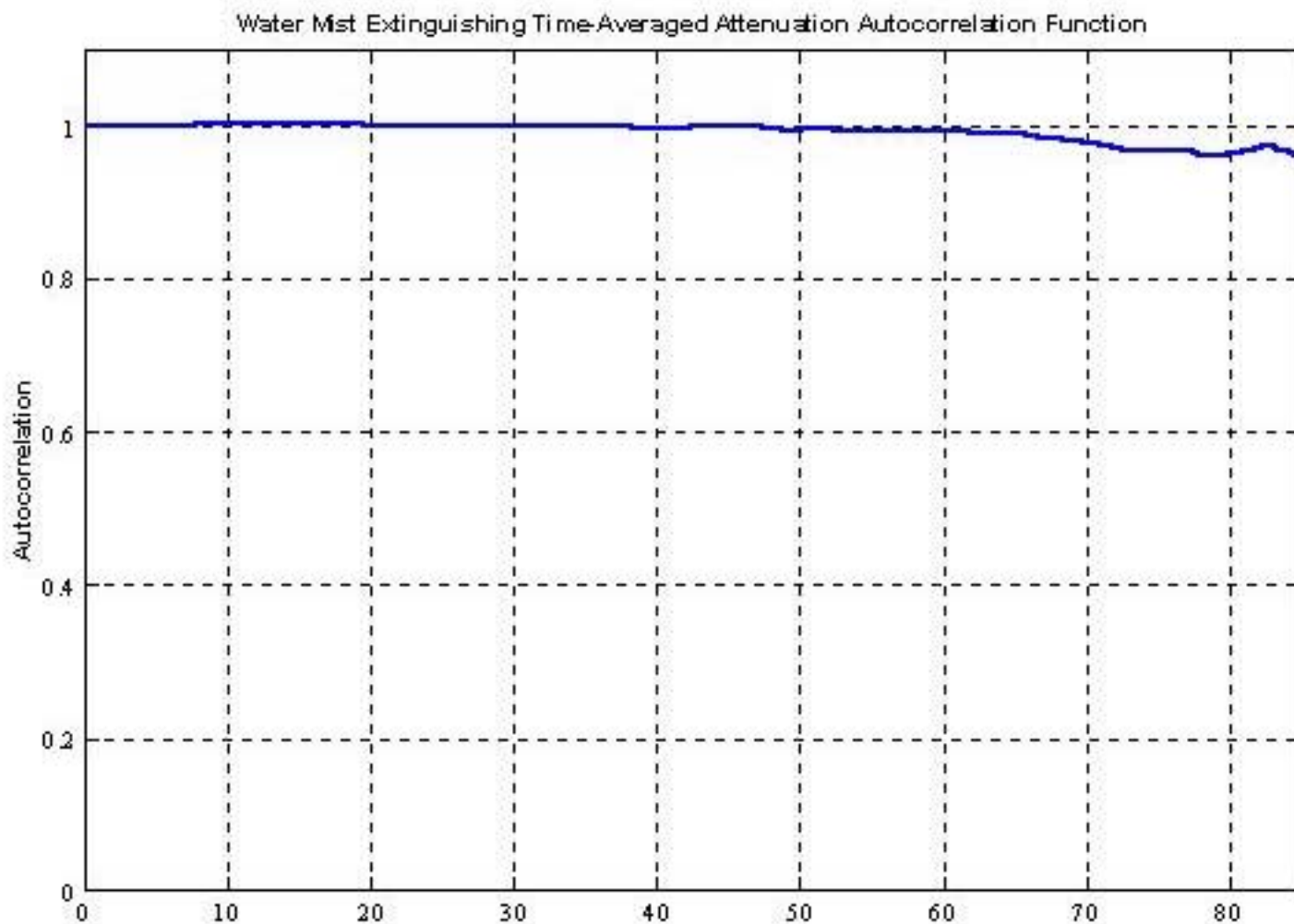


Diesel Fire Normalized Autocorrelation Function for Directional Antennas, H-Pol



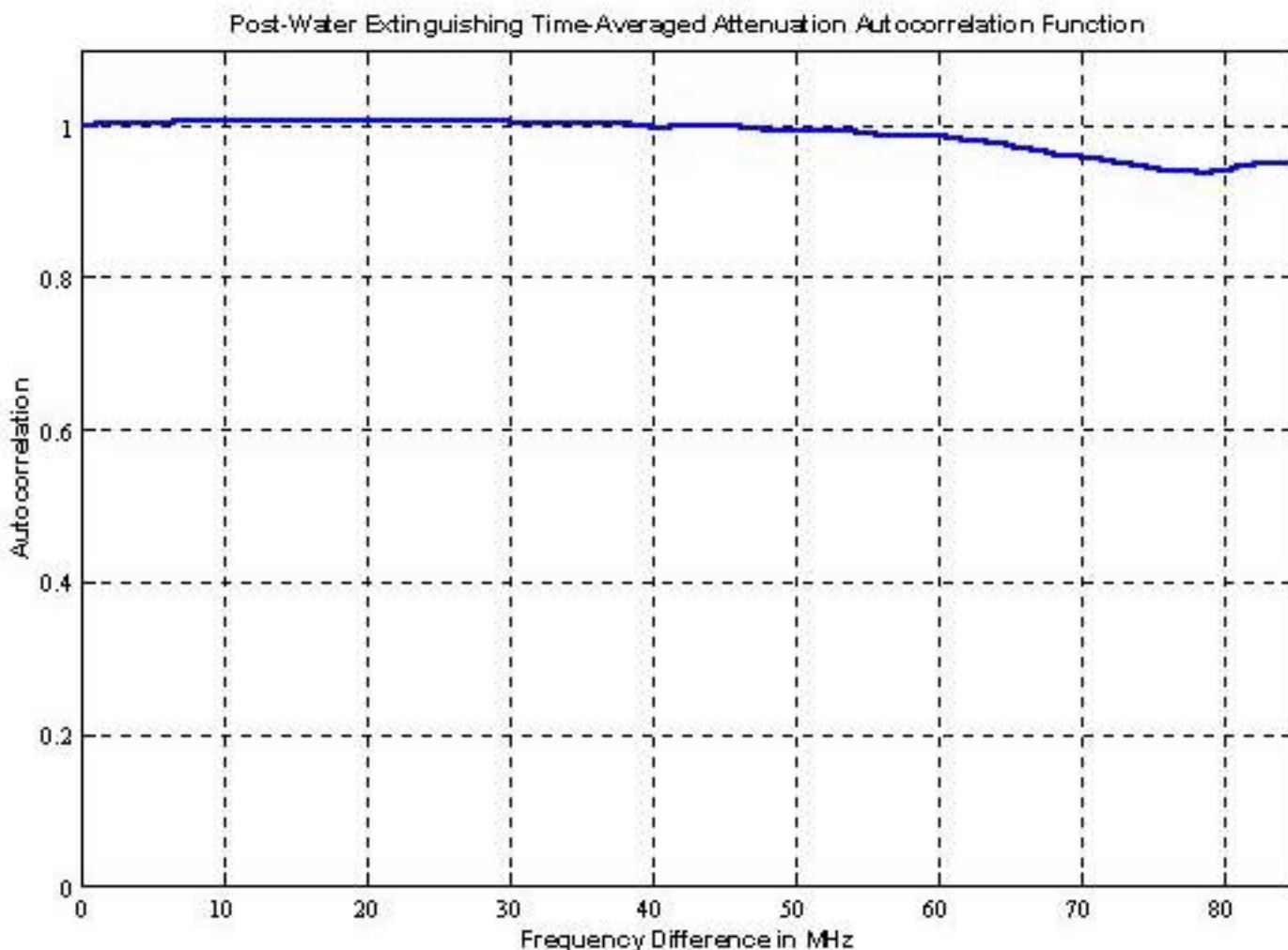


Water Mist Extinguishing Normalized Autocorrelation Function for Directional Antennas, H-Pol





Post-Water Mist Extinguishing Normalized Autocorrelation Function for Directional Antennas, H-Pol





Measurements Summary

- The measurements were performed using a scalar network analyzer by measuring the insertion loss (S_{21}) between the two antennas
- The measurements were automated using a PC with LabView software to control the experiments and collect the data via HP-IB
- Data were taken at 401 frequencies from 2.4 to 2.485 GHz at the rate of 401 data points per 0.8 s

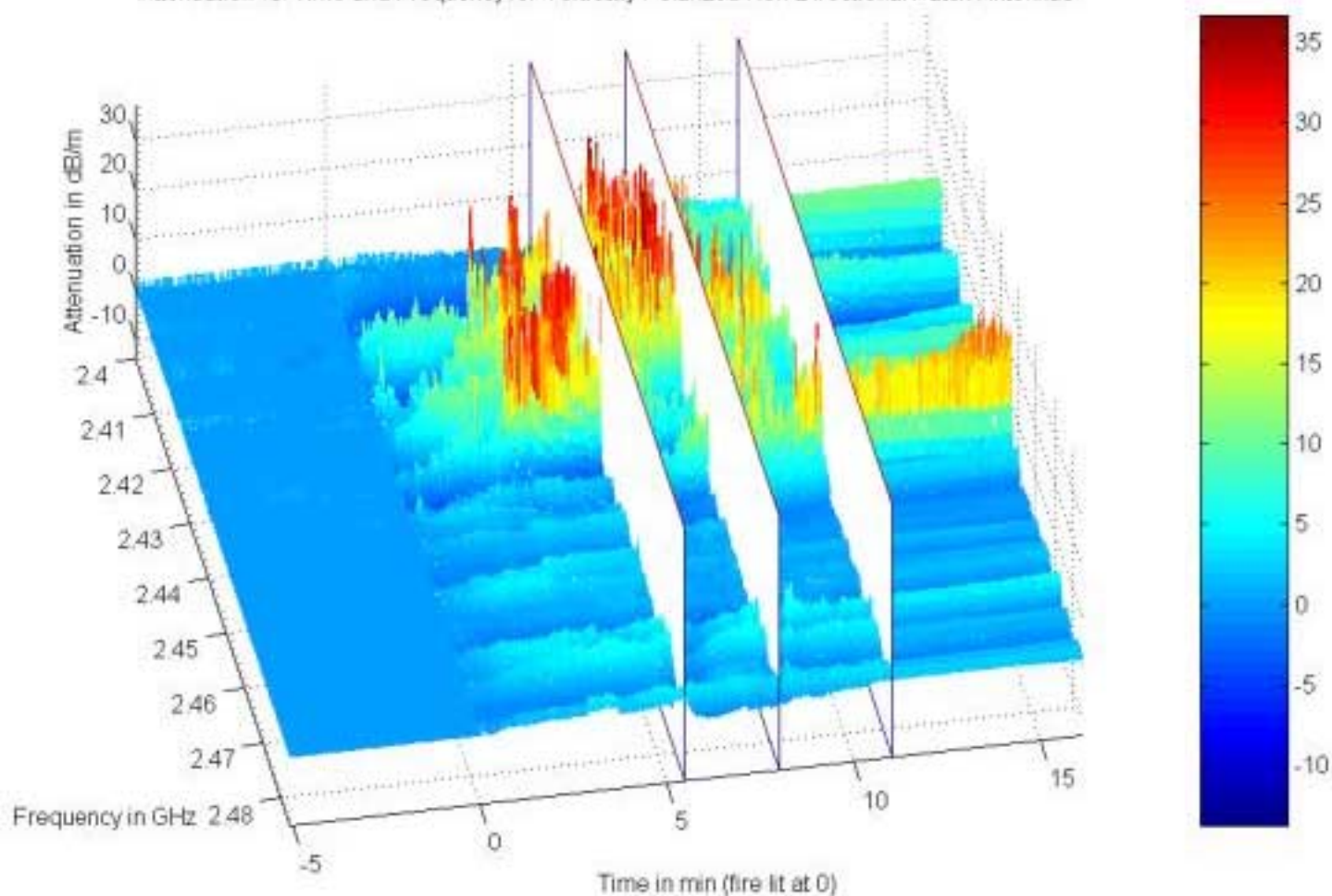


Results for Vertically Polarized Non-Directional Patch Antennas



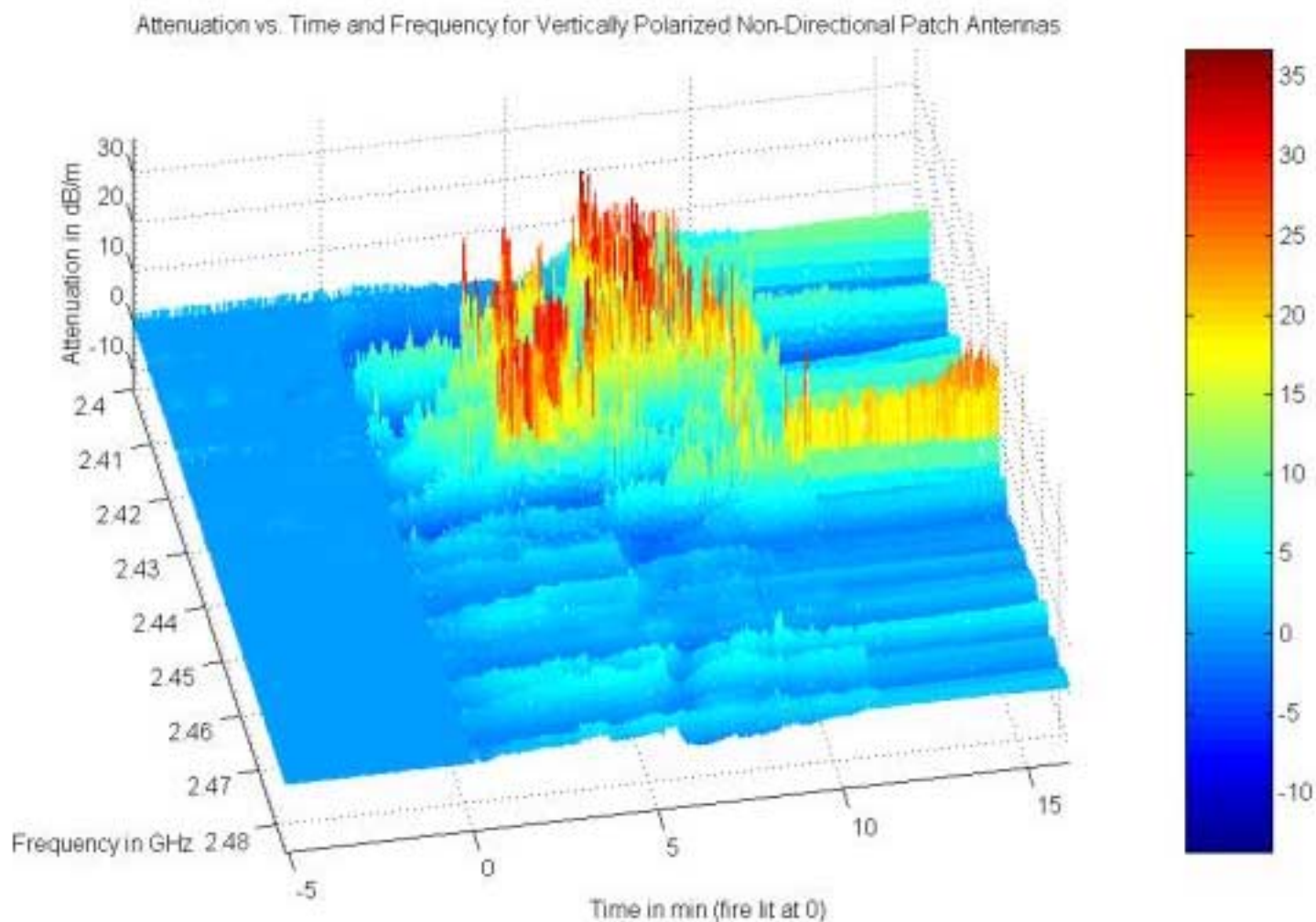
Attenuation for Patch Antennas, V-Pol

Attenuation vs. Time and Frequency for Vertically Polarized Non-Directional Patch Antennas



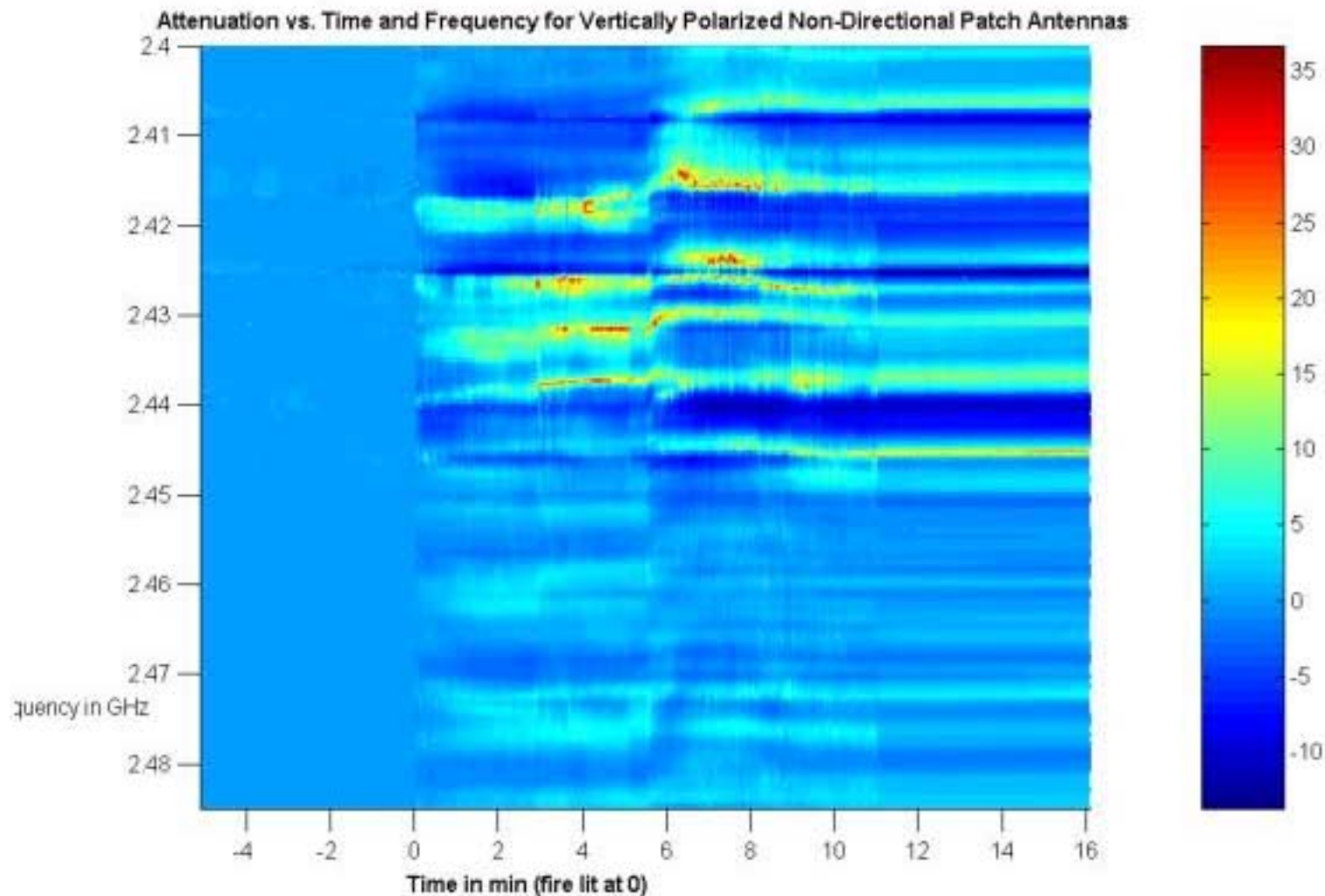


Attenuation for Patch Antennas, V-Pol



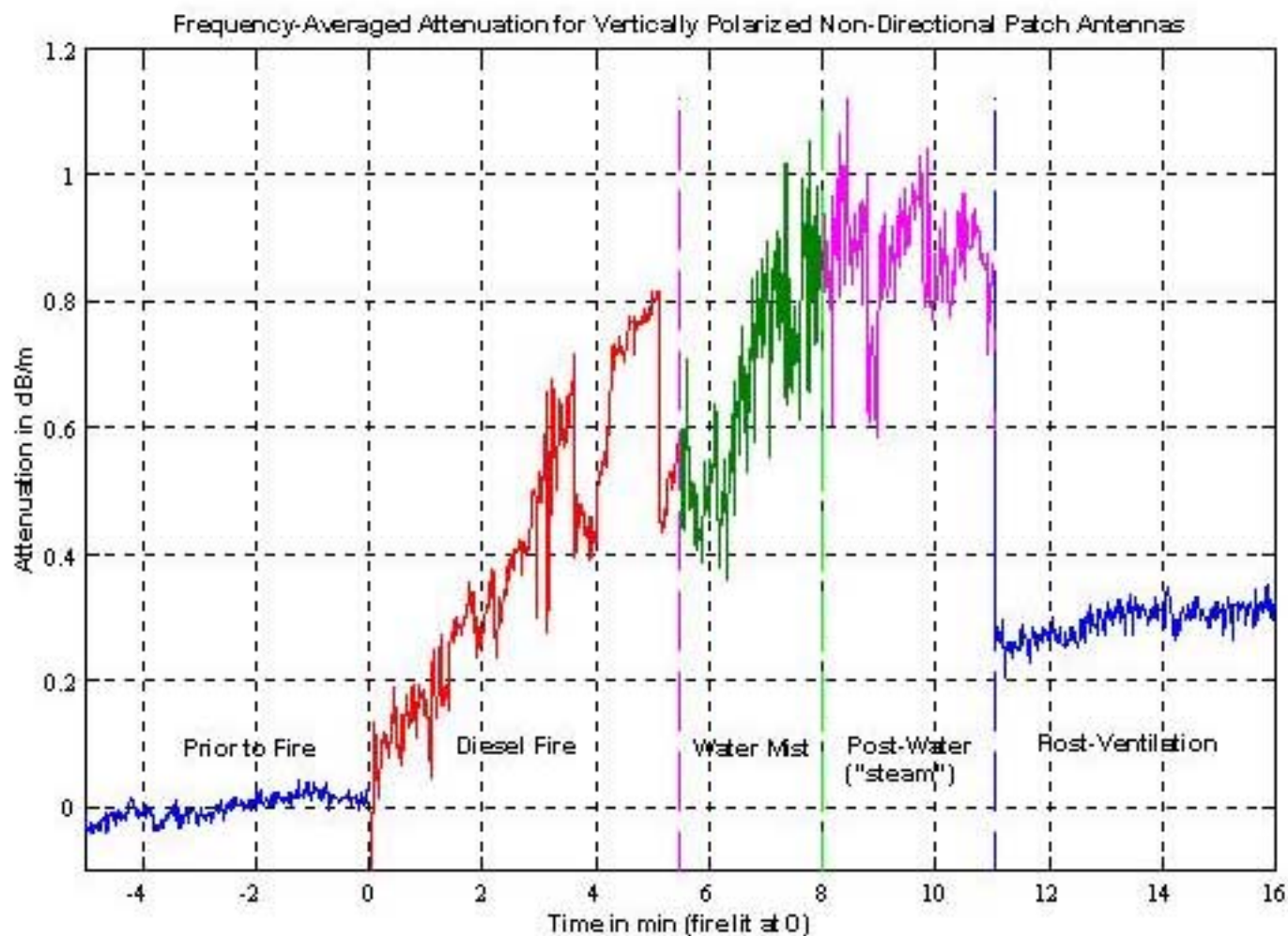


Attenuation for Patch Antennas, V-Pol



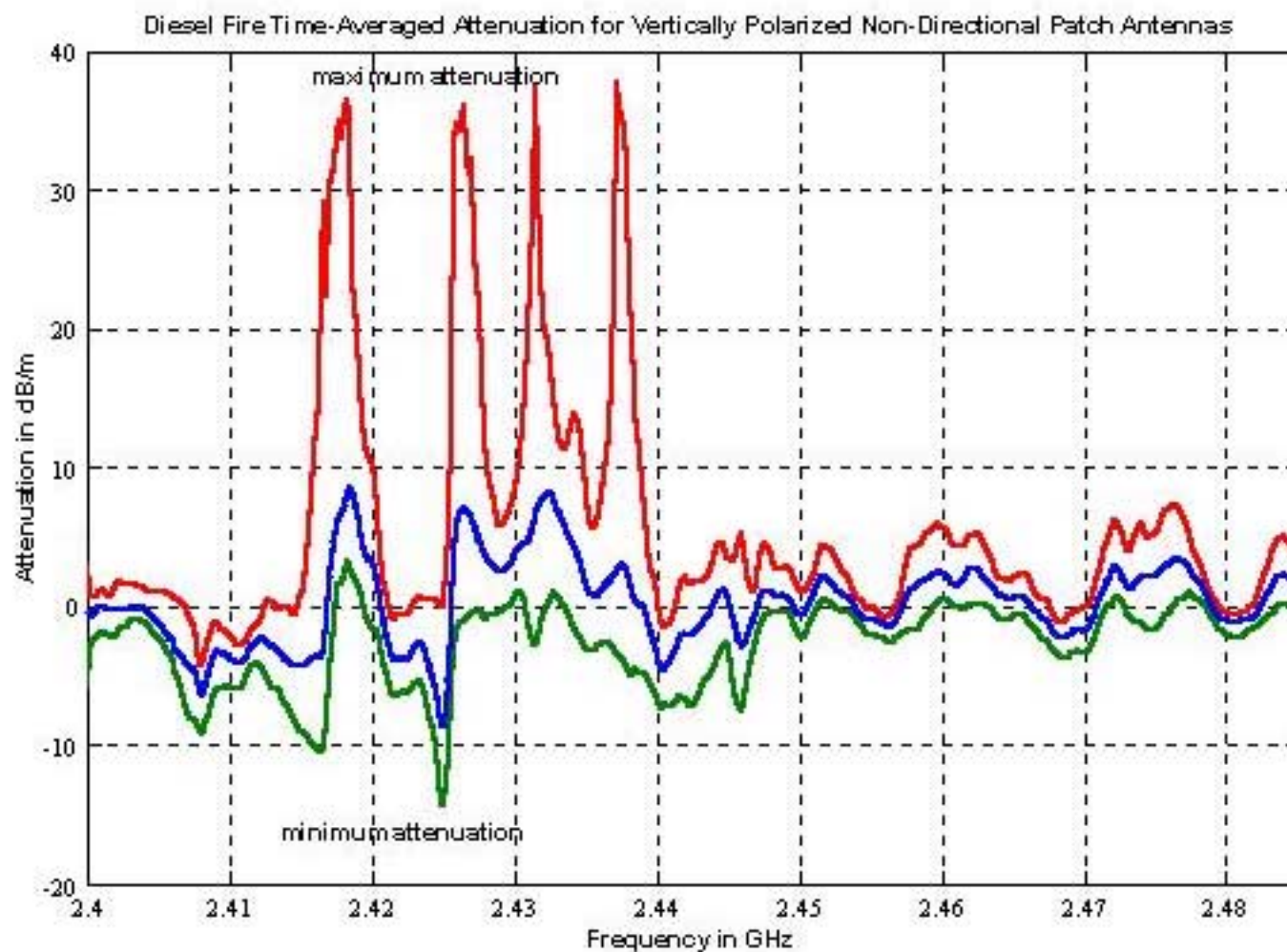


Frequency-Averaged Attenuation for Patch Antennas, V-Pol





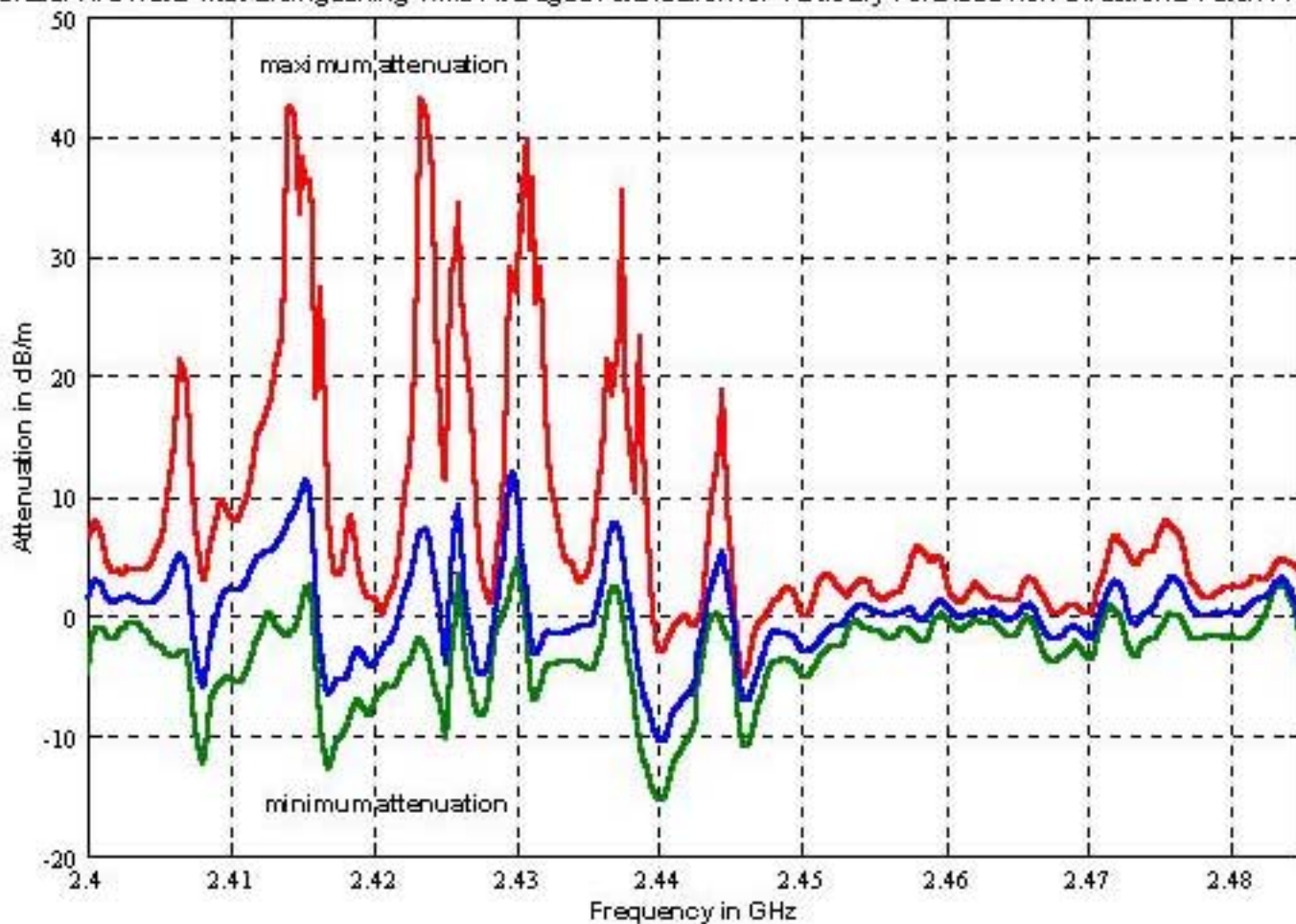
Diesel Fire Attenuation for Patch Antennas, V-Pol





Water Mist Extinguishing Attenuation for Patch Antennas, V-Pol

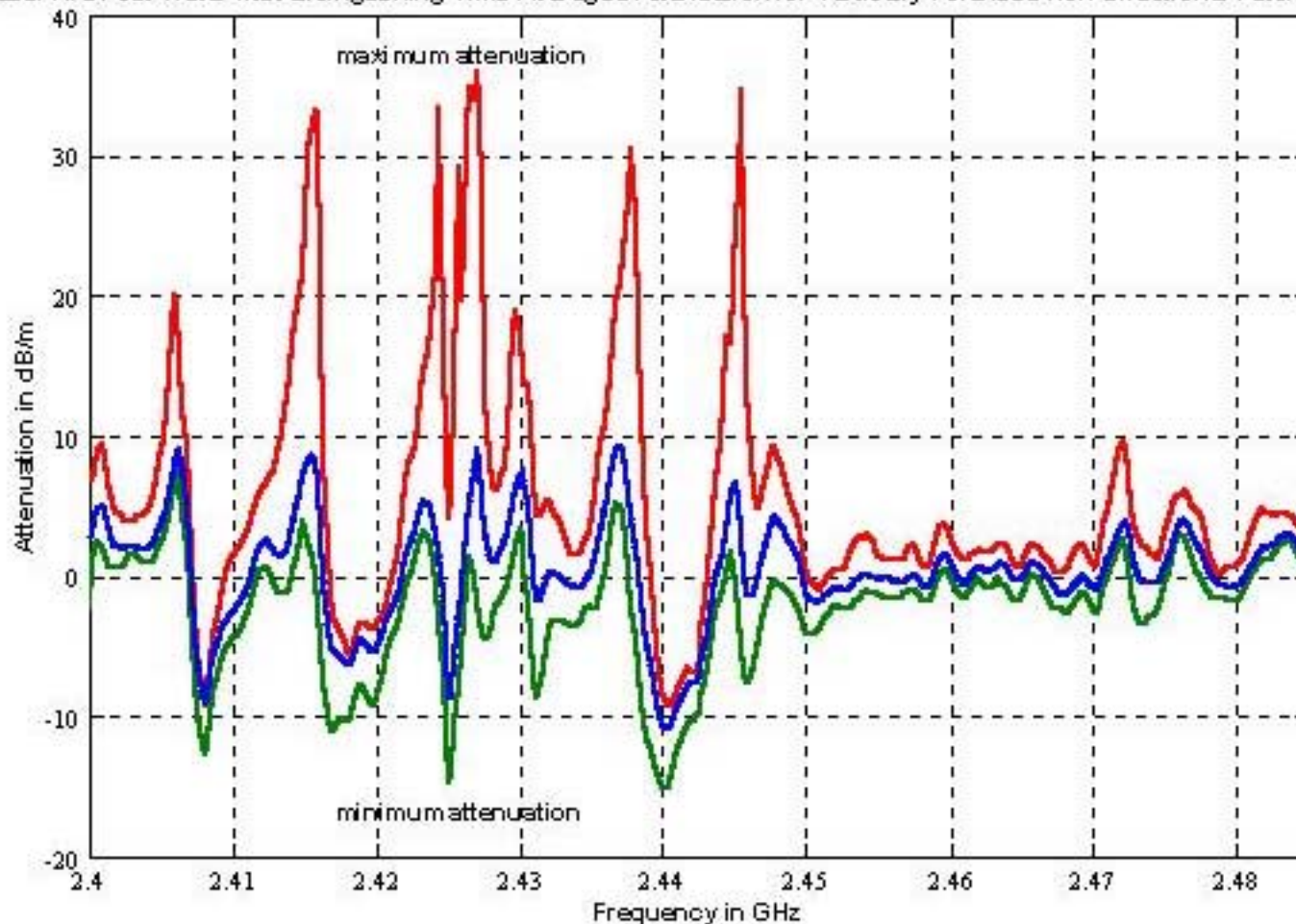
Diesel Fire Water Mist Extinguishing Time-Averaged Attenuation for Vertically Polarized Non-Directional Patch Antennas





Post-Water Mist Extinguishing Attenuation for Patch Antennas, V-Pol

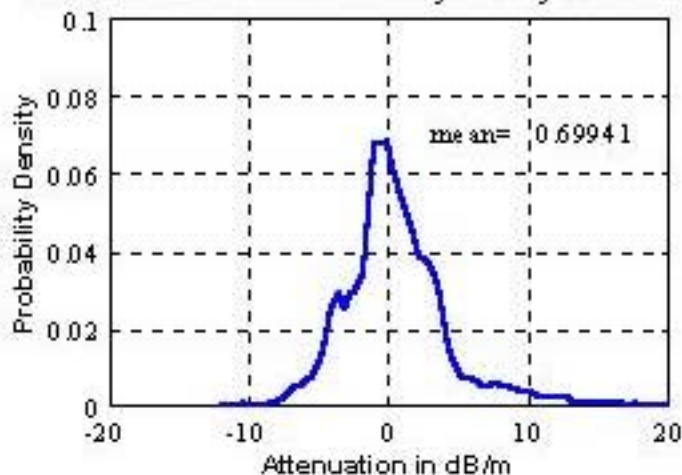
Diesel Fire Post-Water Mist Extinguishing Time-Averaged Attenuation for Vertically Polarized Non-Directional Patch Antennas



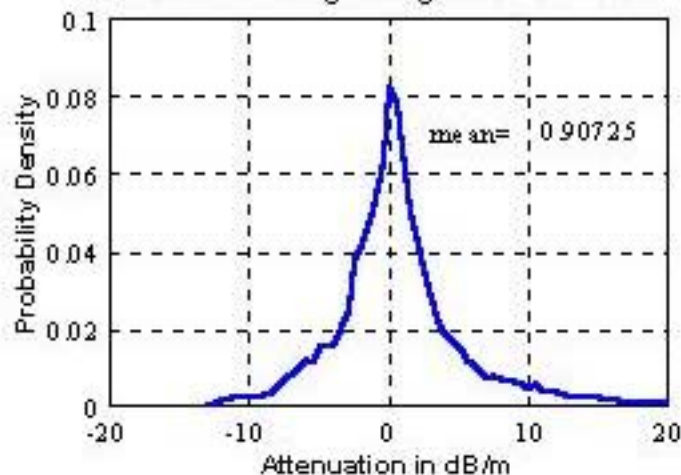


Attenuation Probability Density Functions for Patch Antennas, V-Pol

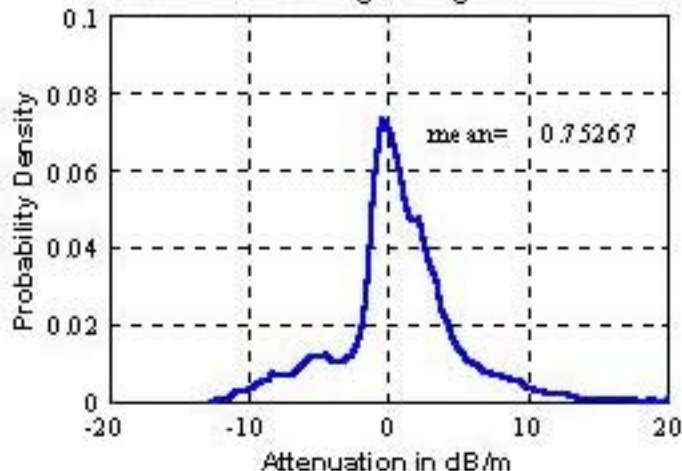
Diesel Fire Attenuation Probability Density Function (PDF)



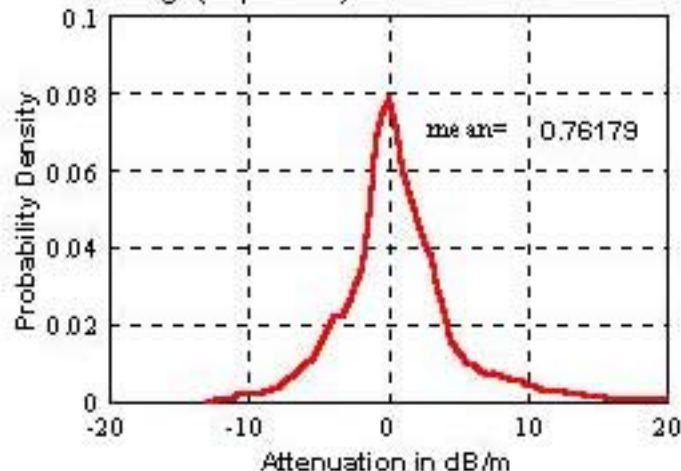
Water Mist Extinguishing Attenuation PDF



Post-Water Mist Extinguishing Attenuation PDF



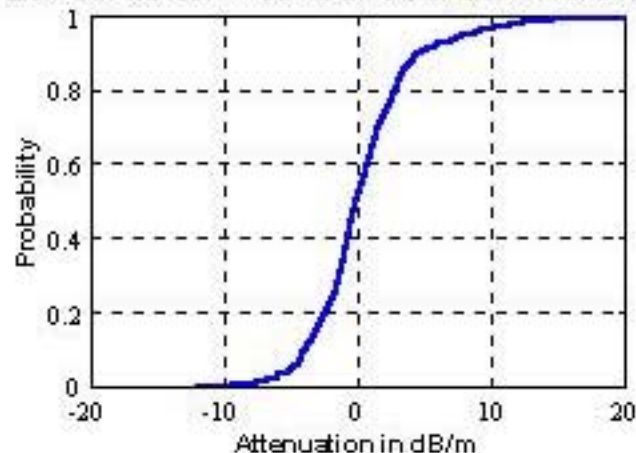
Average (all phases) Attenuation CDF for V-Pol



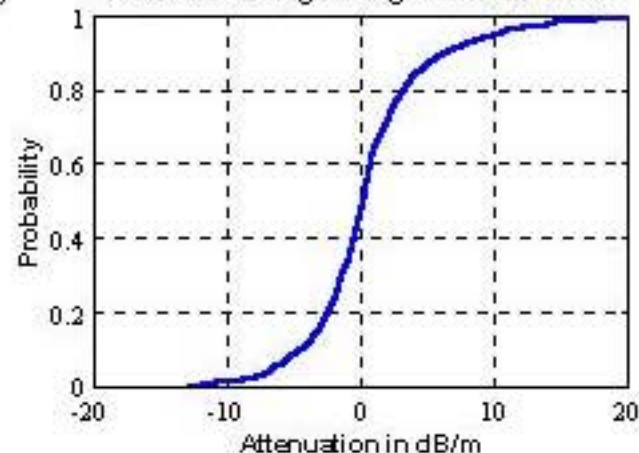


Attenuation Cumulative Distribution Functions for Patch Antennas, V-Pol

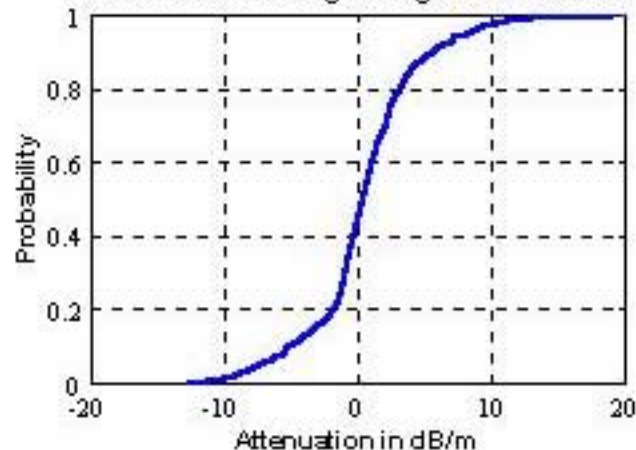
Diesel Fire Attenuation Cumulative Distribution Function (CDF)



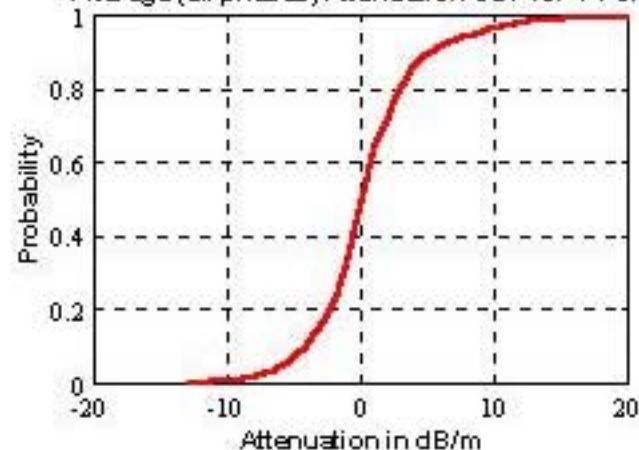
Water Mist Extinguishing Attenuation CDF



Post-Water Mist Extinguishing Attenuation CDF



Average (all phases) Attenuation CDF for V-Pol



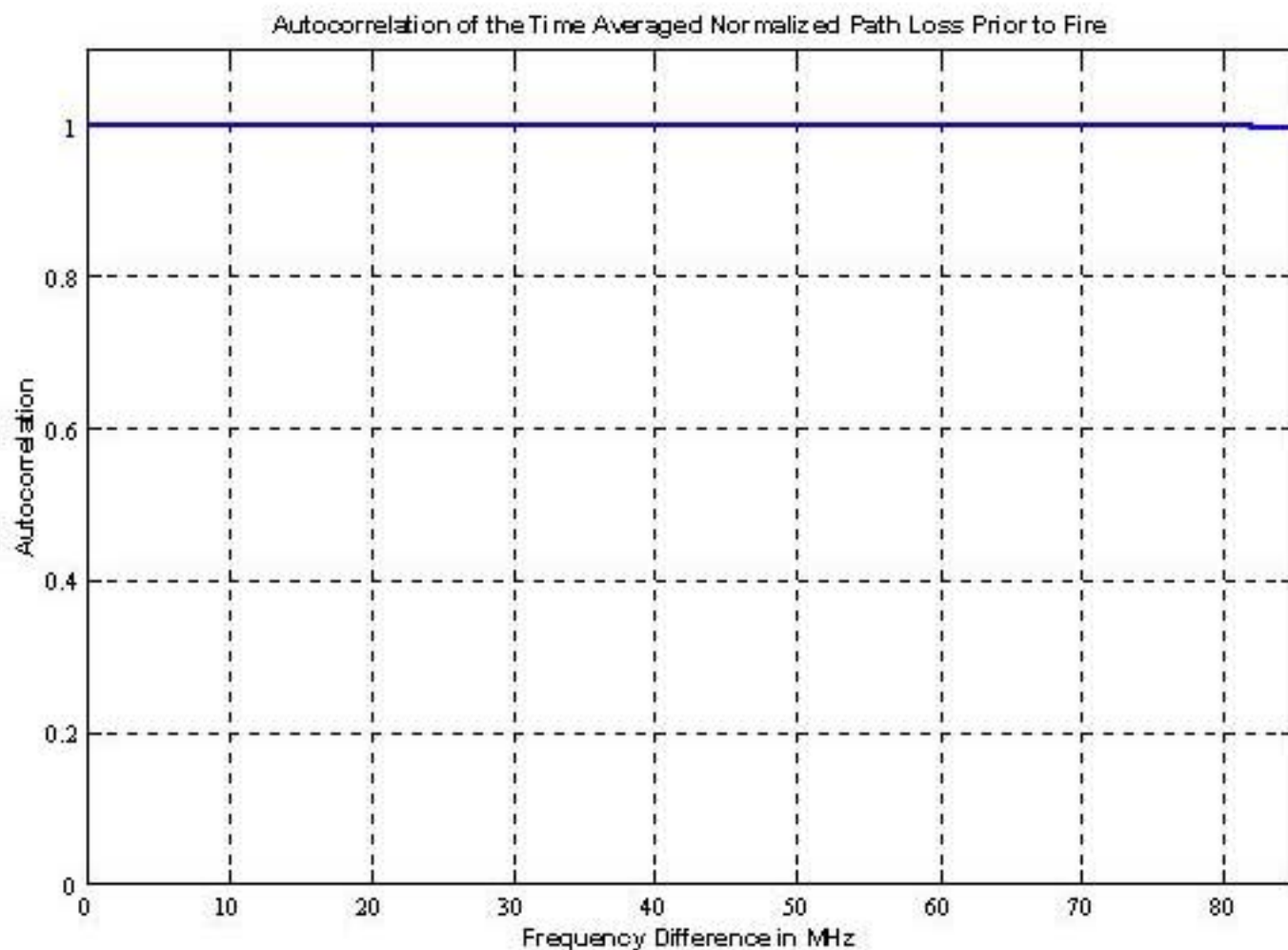


Measurements Summary

- In order to achieve a sufficiently high signal-to-noise ratio a TWT amplifier with 30 dB of gain was used with the low gain (patch) antennas
- The antennas were positioned in the "simulated" machine space such that the "fire source" was approximately half-way between the transmitting and the receiving antenna
- The measurement equipment was set up in the "engineering station" compartment adjacent to the "machine" space where hydrocarbon fuel fires (diesel and heptane) were set

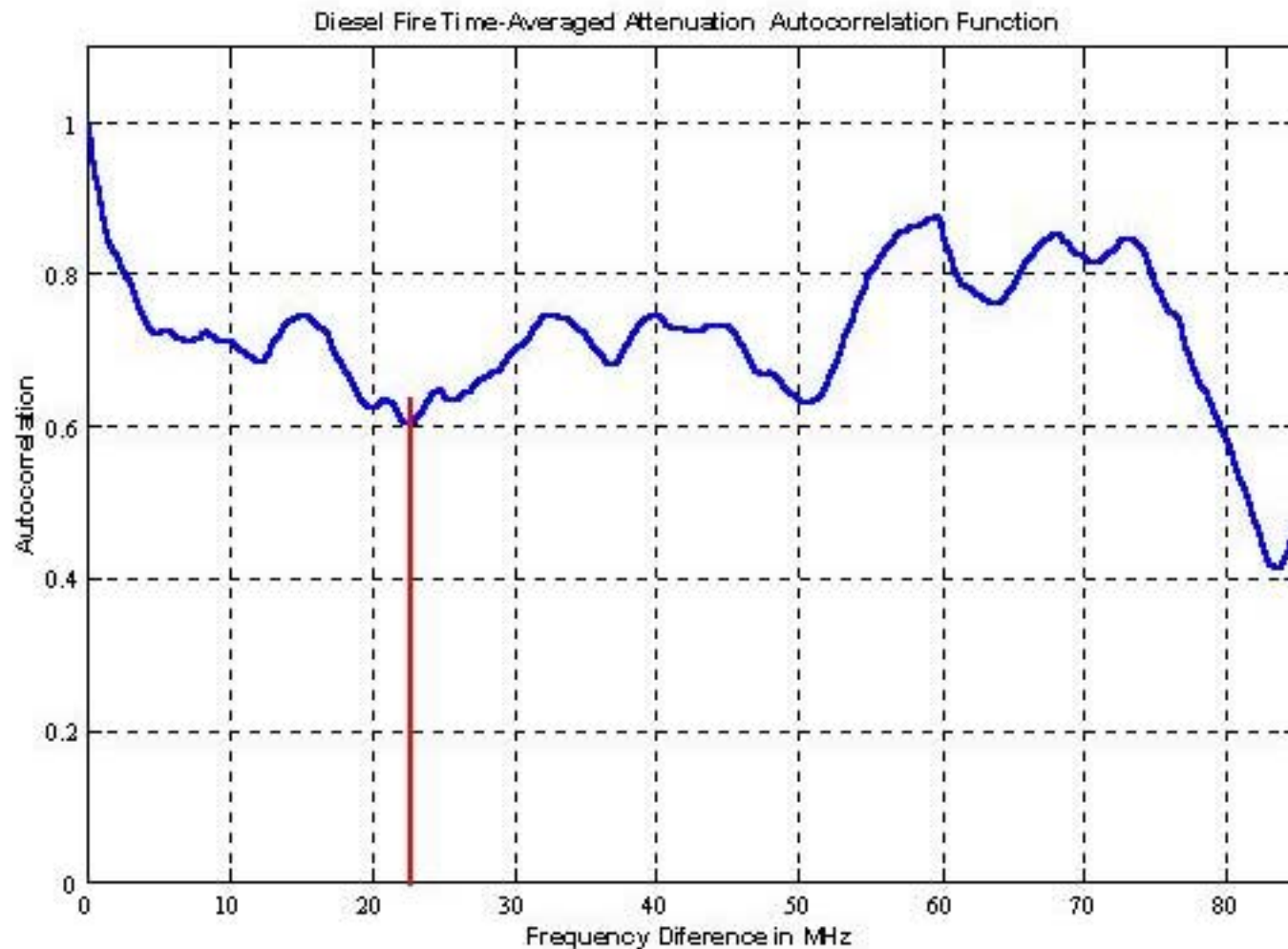


Normalized Autocorrelation Function for Patch Antennas Prior to Fire, V-Pol



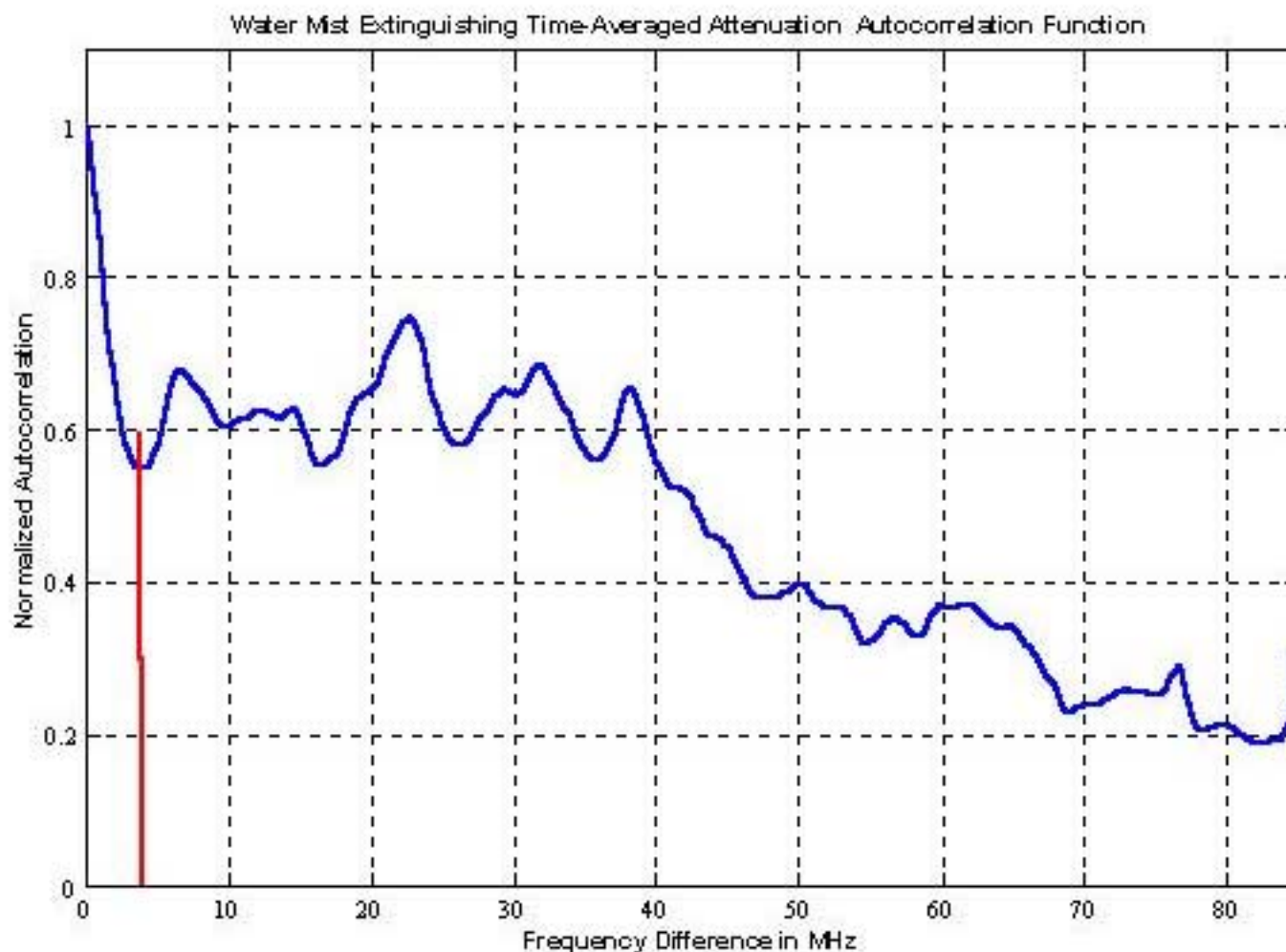


Diesel Fire Normalized Autocorrelation Function for Patch Antennas, V-Pol



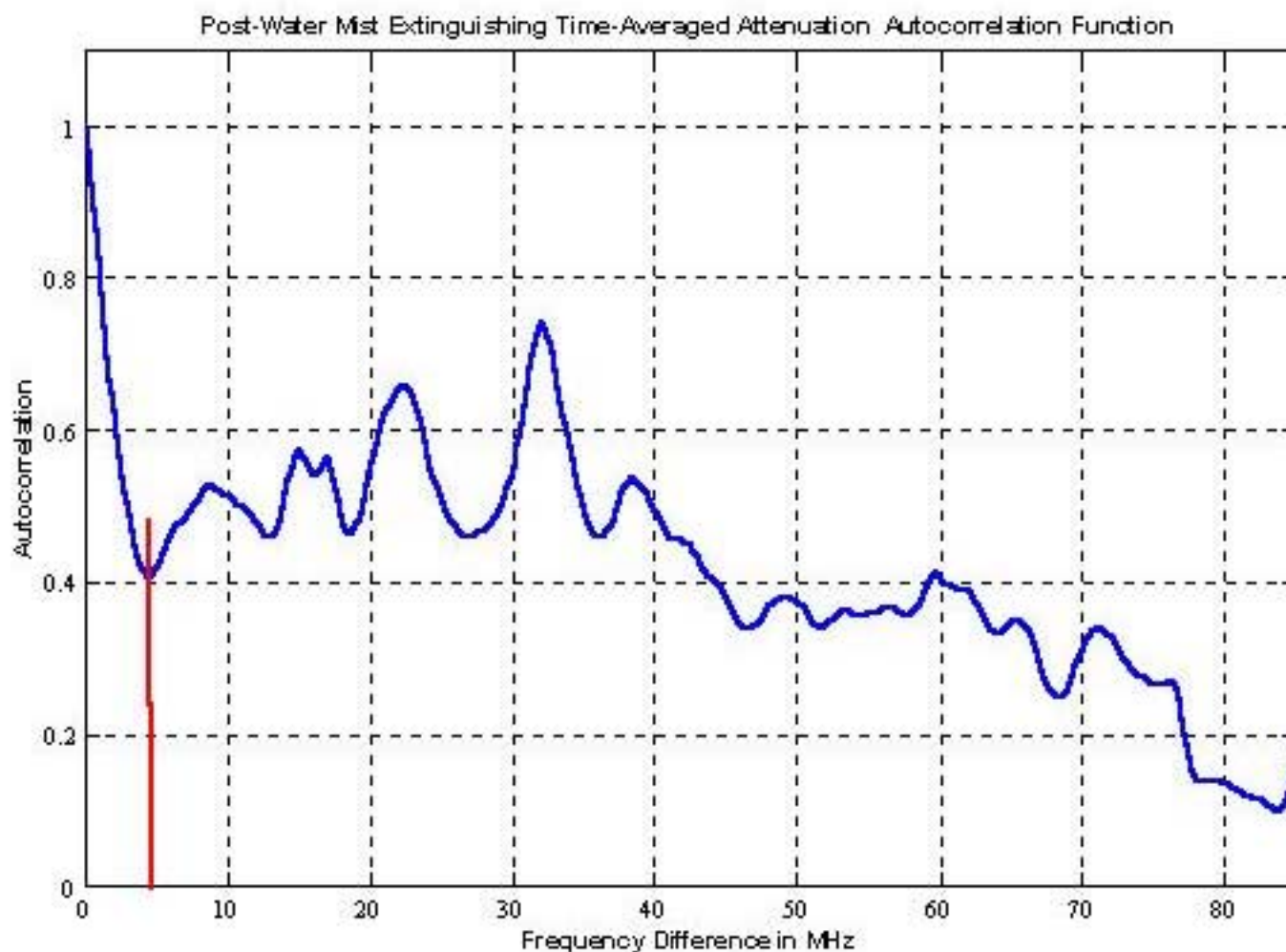


Water Mist Extinguishing Normalized Autocorrelation Function for Patch Antennas, V-Pol





Post-Water Mist Extinguishing Normalized Autocorrelation Function for Patch Antennas, V-Pol



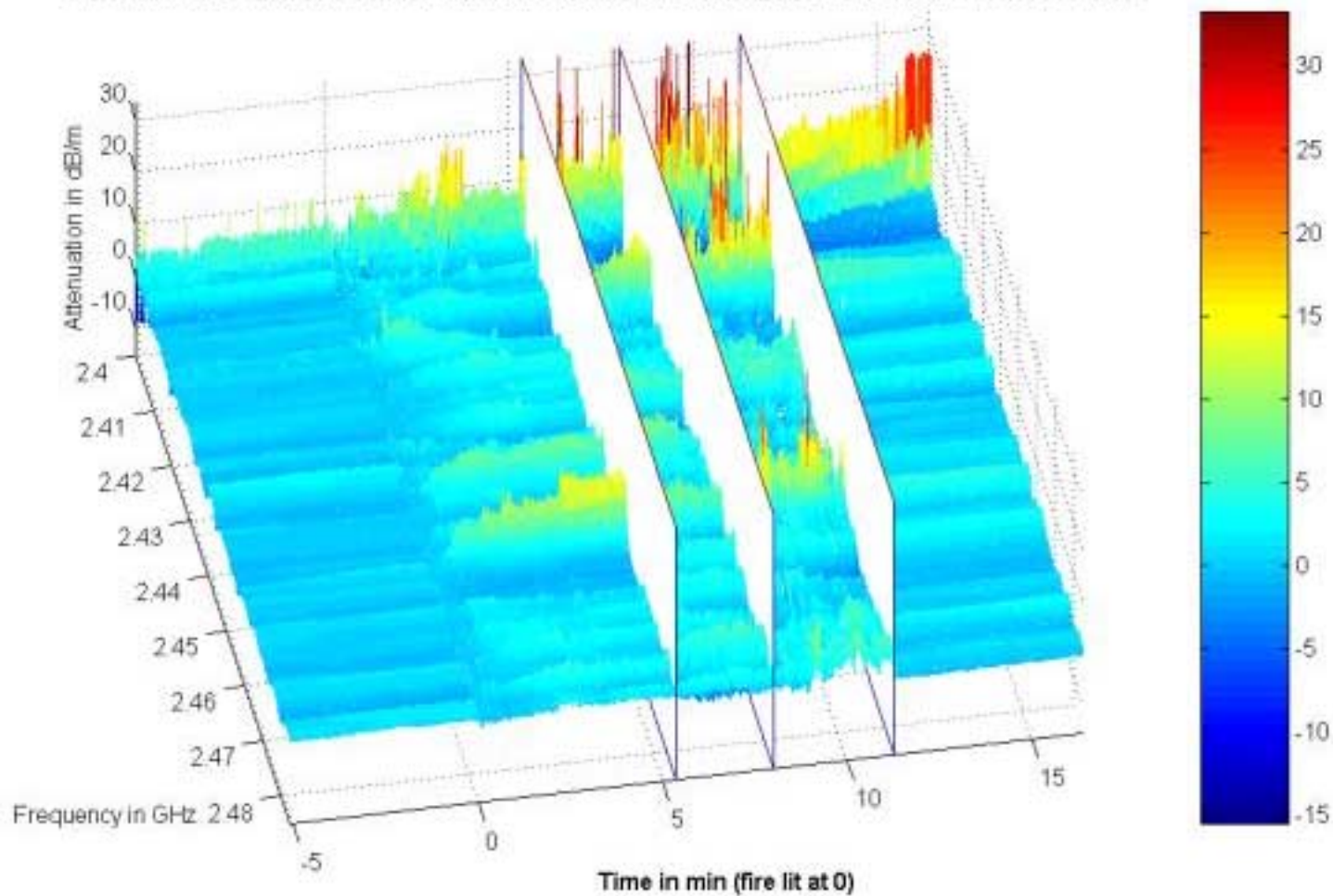


Results for Horizontally Polarized Non-Directional Patch Antennas



Attenuation for Patch Antennas, H-Pol

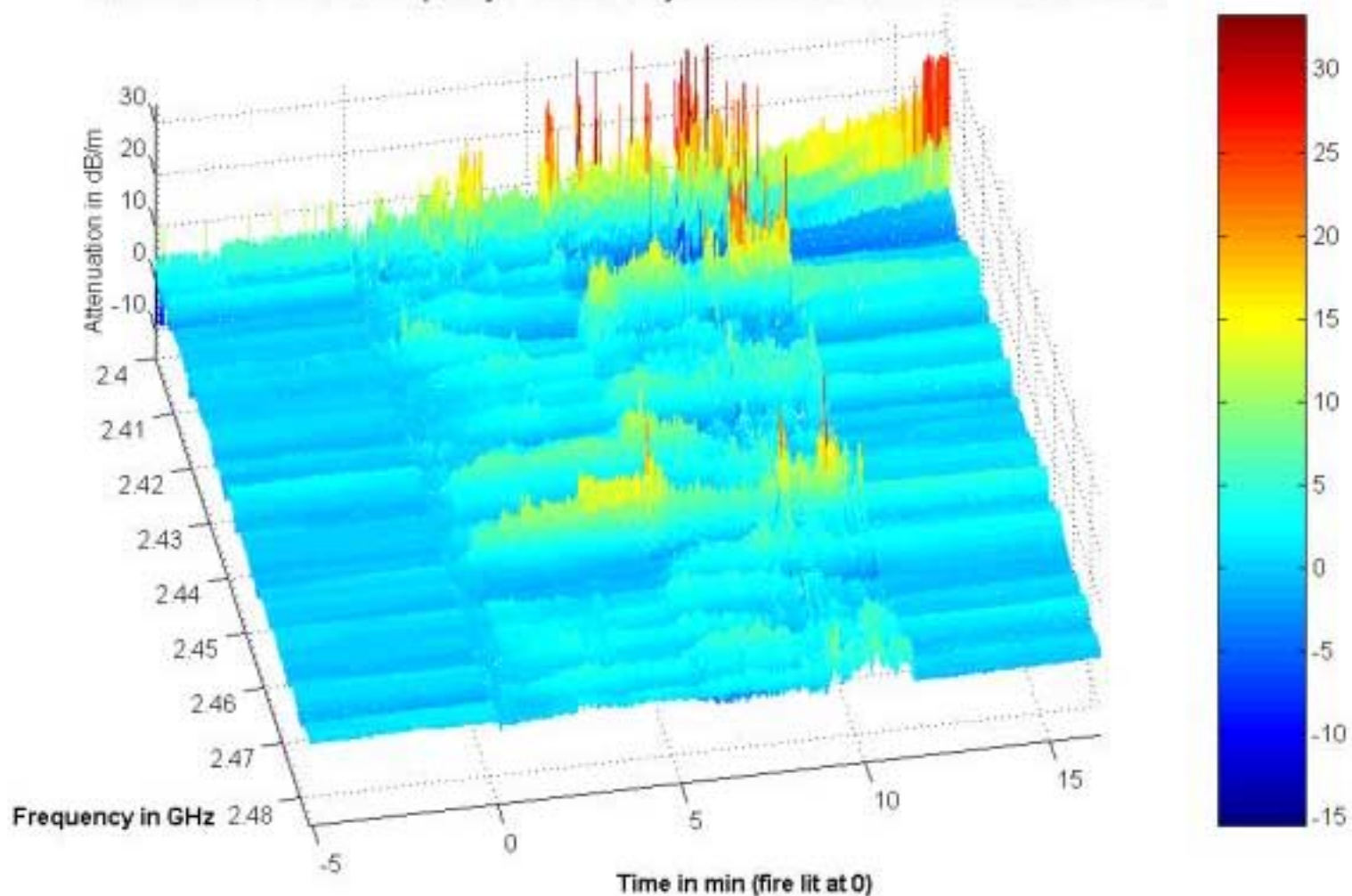
Attenuation vs Time and Frequency for Horizontally Polarized Non-Directional Patch Antennas





Attenuation for Patch Antennas, H-Pol

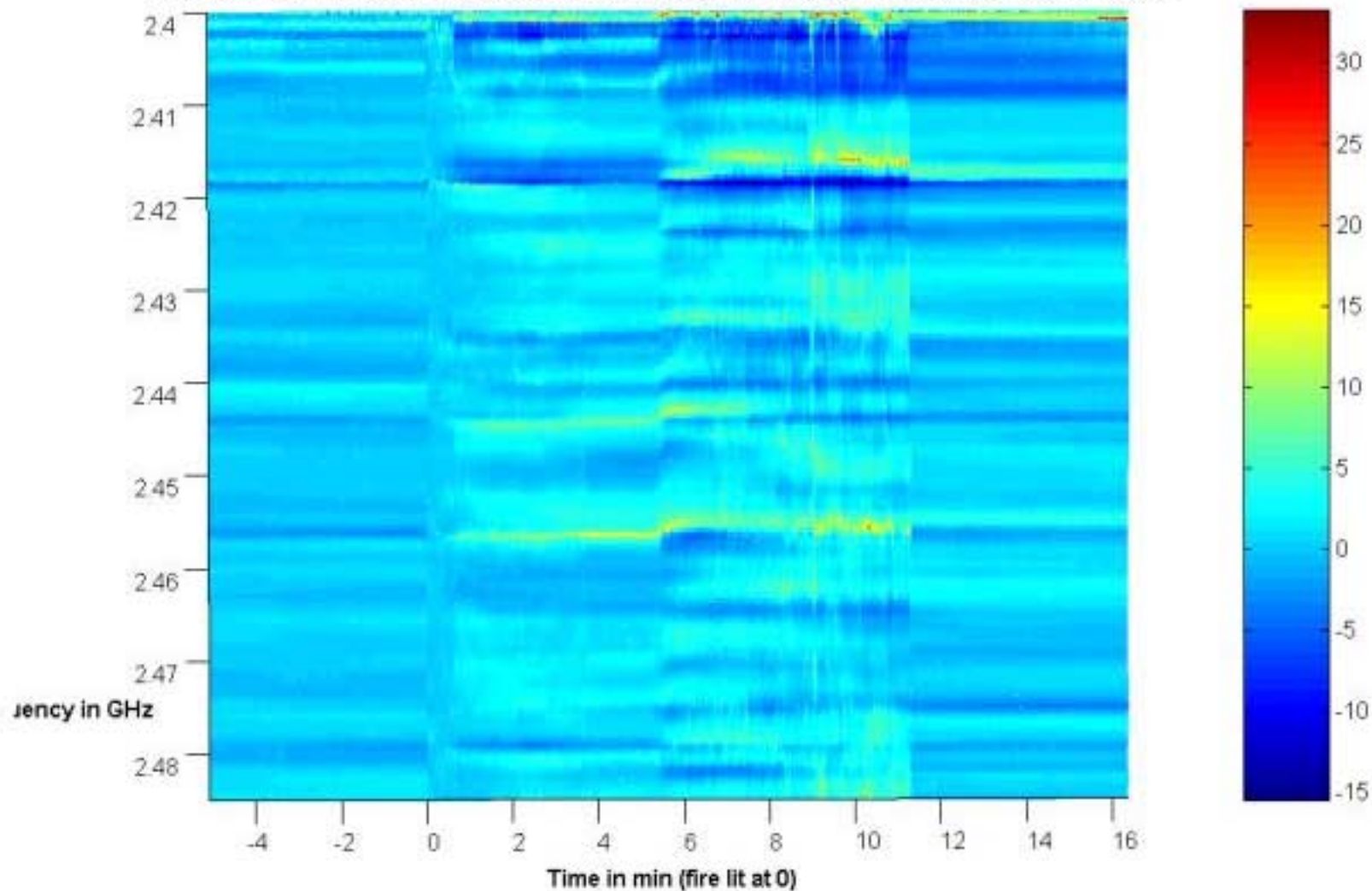
Attenuation vs. Time and Frequency for Horizontally Polarized Non-Directional Patch Antennas





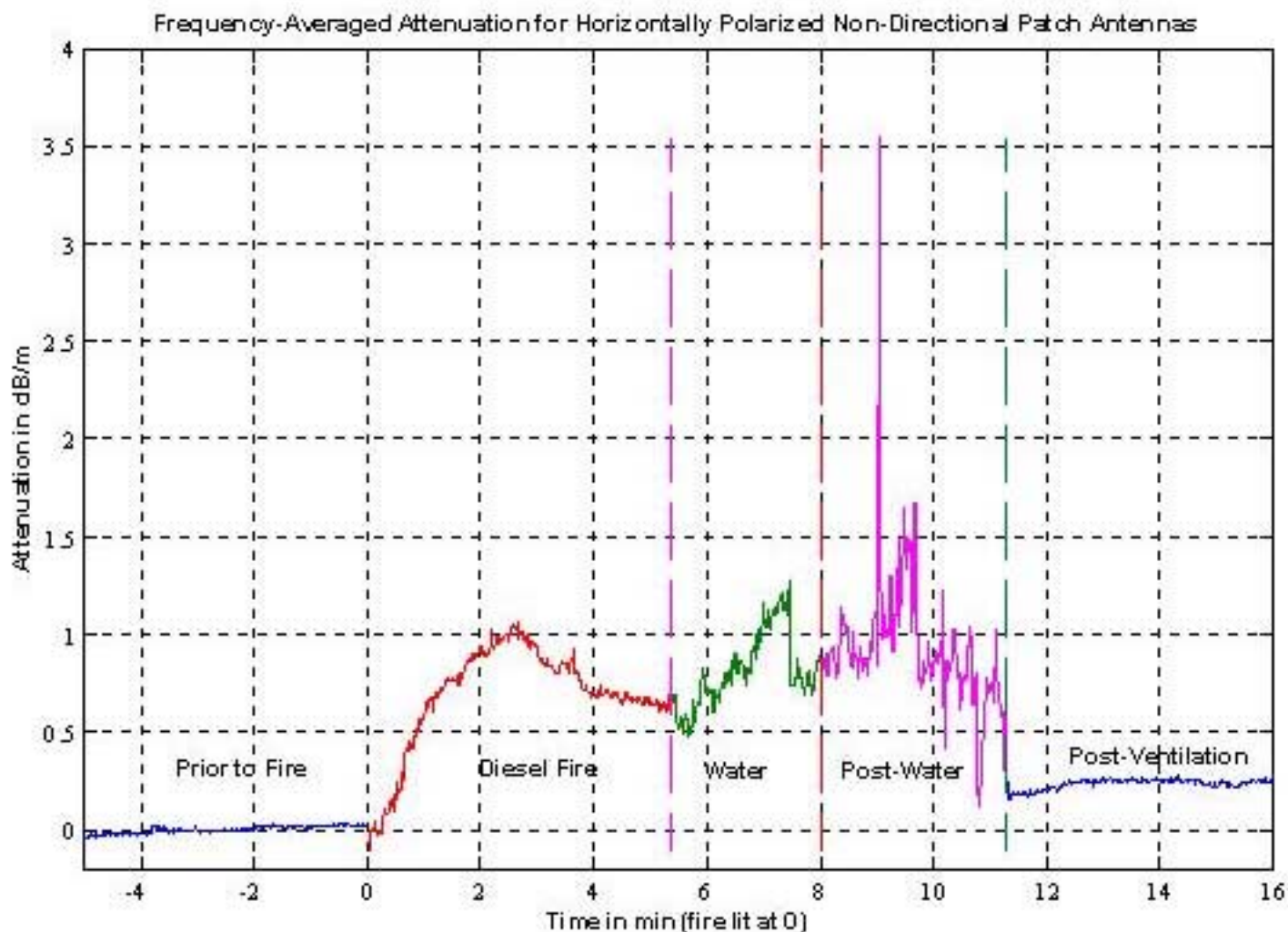
Attenuation for Patch Antennas, H-Pol

Attenuation vs. Time and Frequency for Horizontally Polarized Non-Directional Patch Antennas



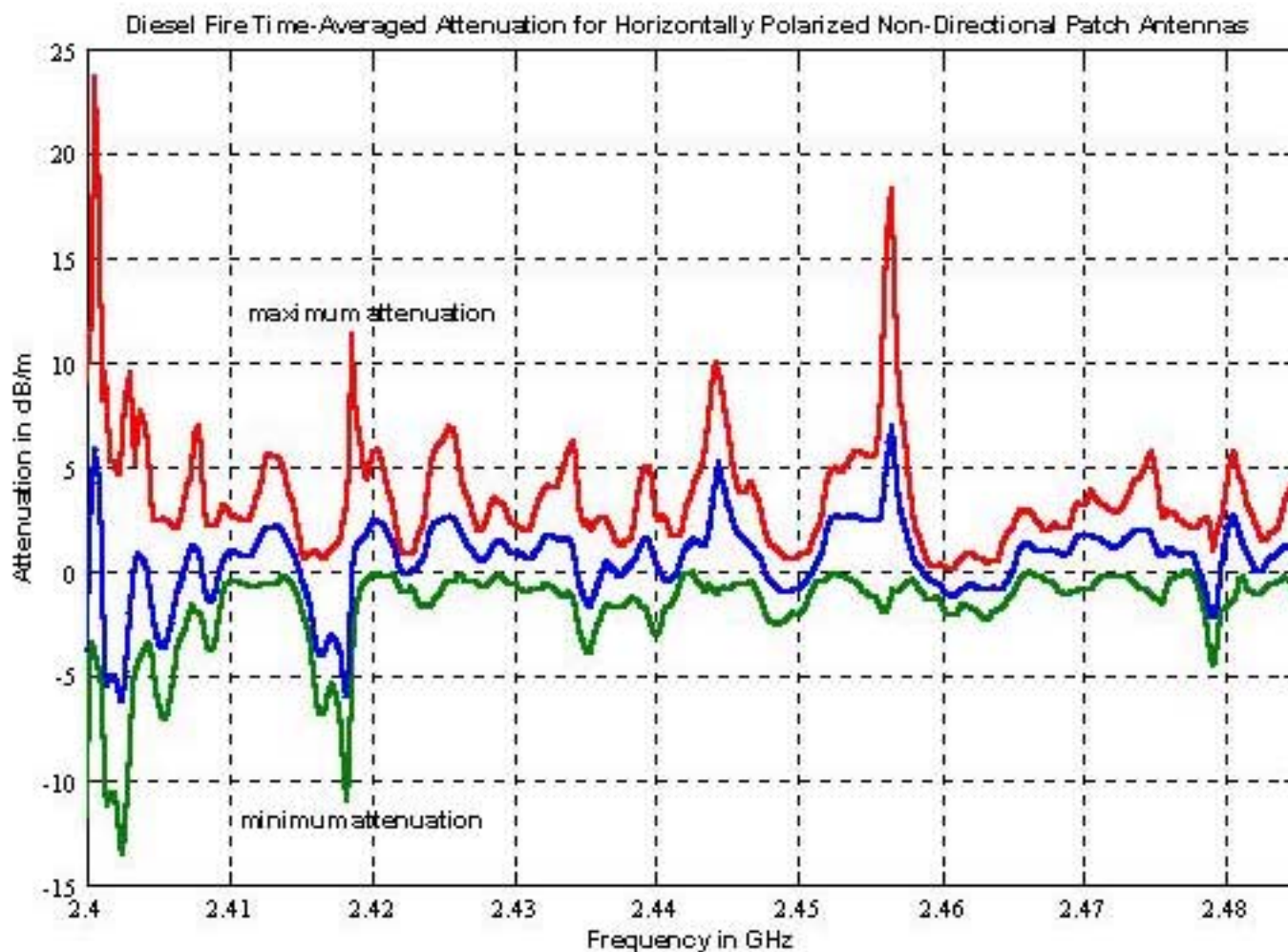


Frequency-Averaged Attenuation for Patch Antennas, H-Pol





Diesel Fire Attenuation for Patch Antennas, H-Pol





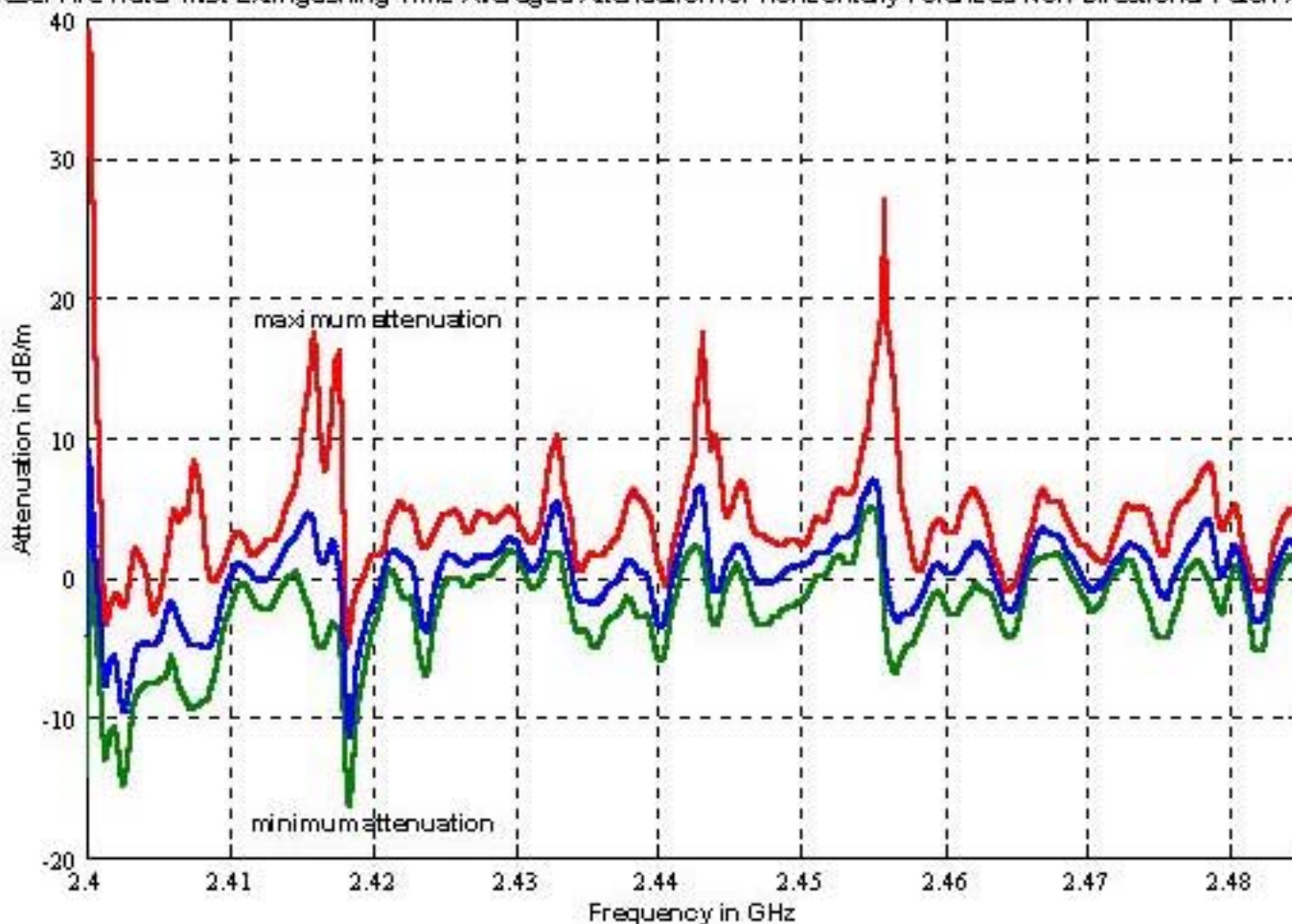
Measurements Summary

- The insertion loss was measured without (the "reference") and with fire/water between the antennas and the attenuation due to fire/water calculated based on the differences in the measured insertion losses
- Analysis of the measured data was performed at the NPS and is presented in this document



Water Mist Extinguishing Attenuation for Patch Antennas, H-Pol

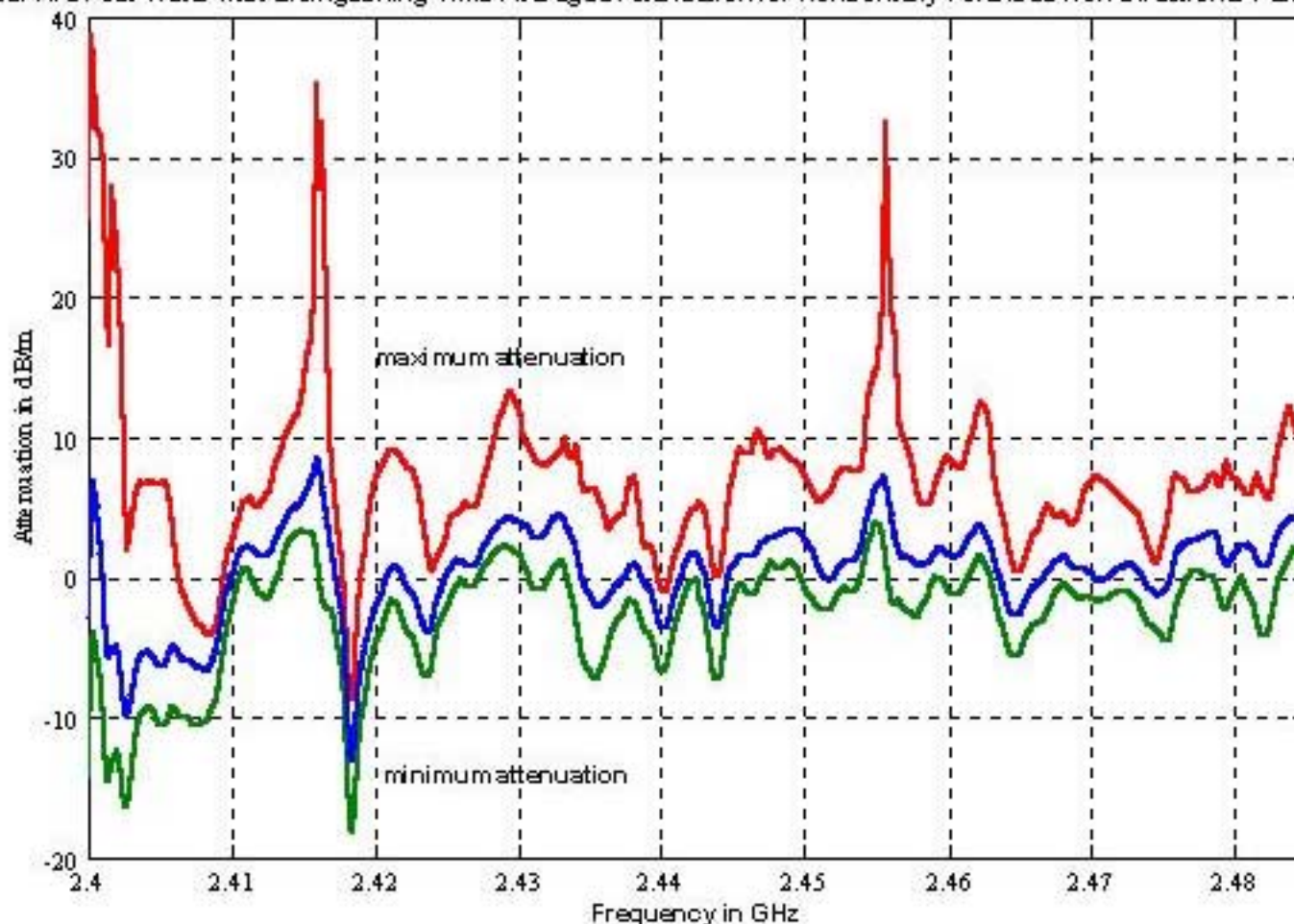
Diesel Fire Water Mist Extinguishing Time-Averaged Attenuation for Horizontally Polarized Non-Directional Patch Antennas





Post-Water Mist Extinguishing Attenuation for Patch Antennas, H-Pol

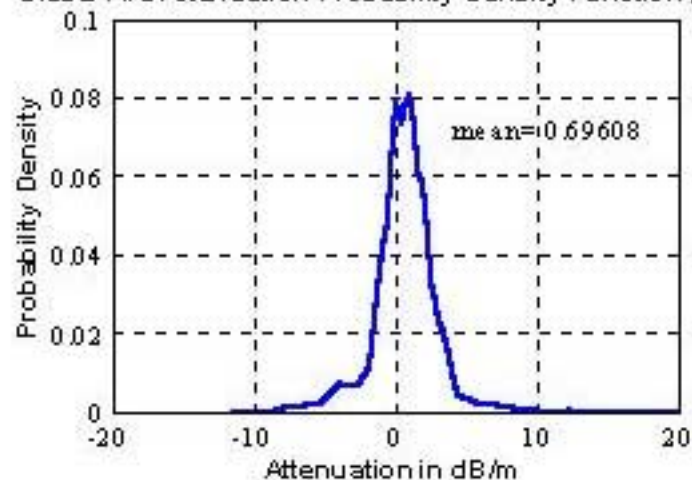
Diesel Fire Post-Water Mist Extinguishing Time-Averaged Attenuation for Horizontally Polarized Non-Directional Patch Antennas



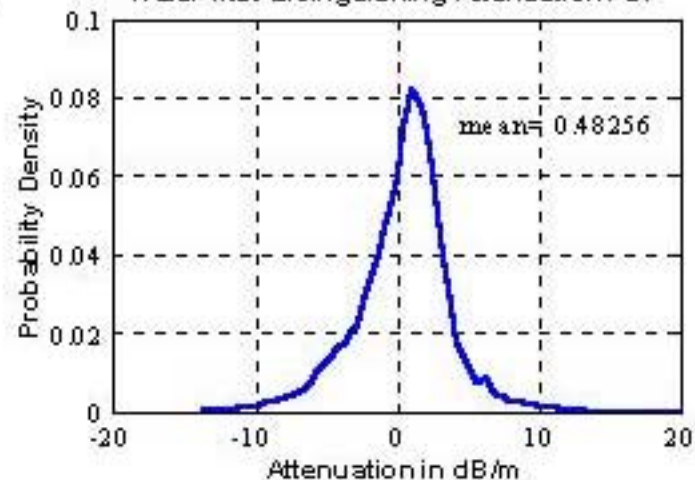


Attenuation Probability Density Functions for Patch Antennas, H-Pol

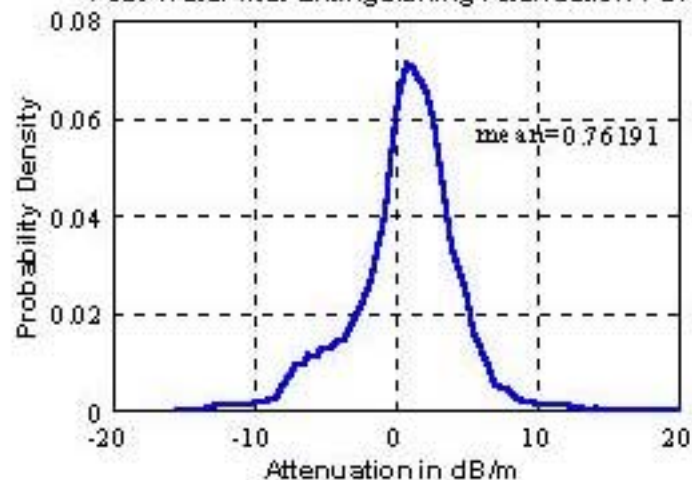
Diesel Fire Attenuation Probability Density Function (PDF)



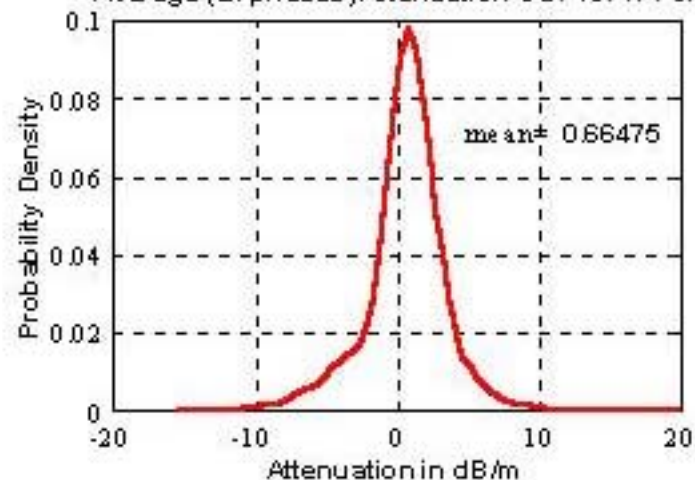
Water Mist Extinguishing Attenuation PDF



Post-Water Mist Extinguishing Attenuation PDF



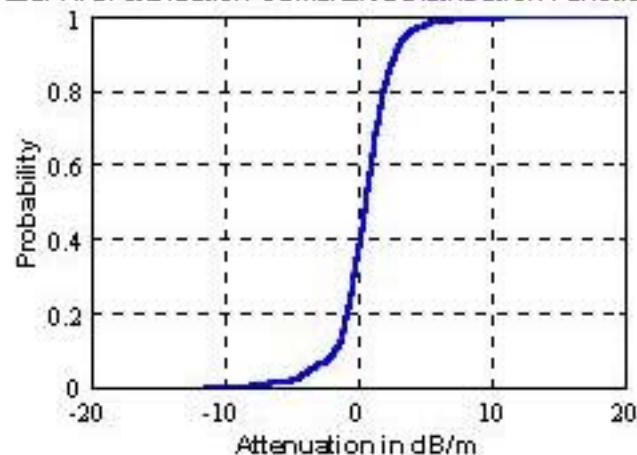
Average (all phases) Attenuation CDF for H-Pol



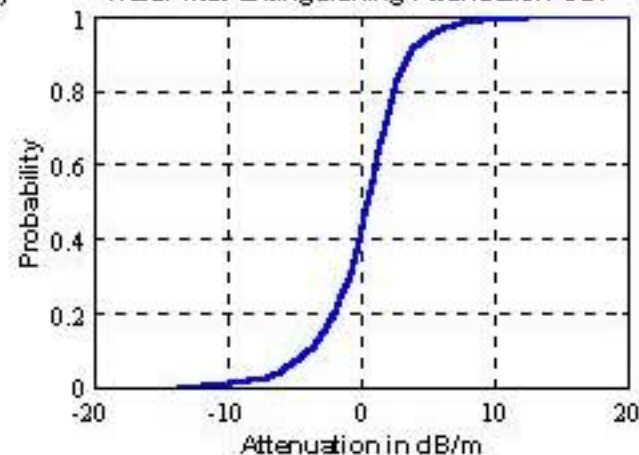


Attenuation Cumulative Distribution Functions for Patch Antennas, H-Pol

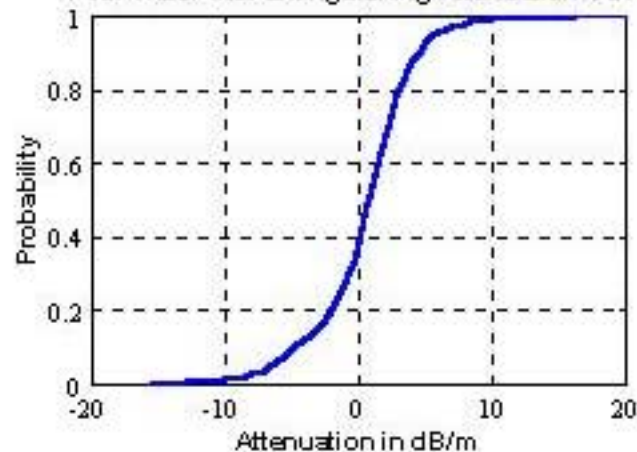
Diesel Fire Attenuation Cumulative Distribution Function (CDF)



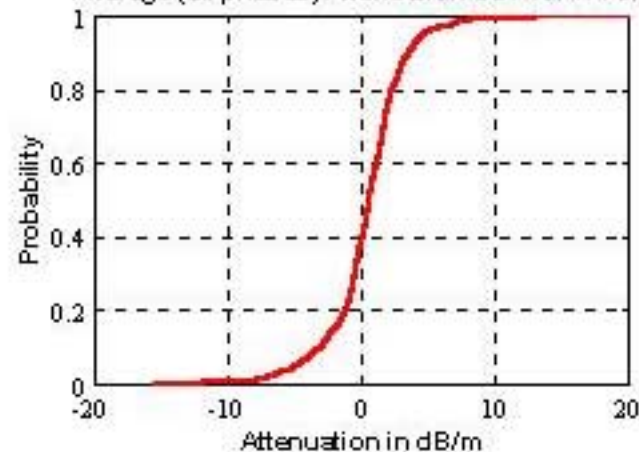
Water Mist Extinguishing Attenuation CDF



Post-Water Mist Extinguishing Attenuation CDF

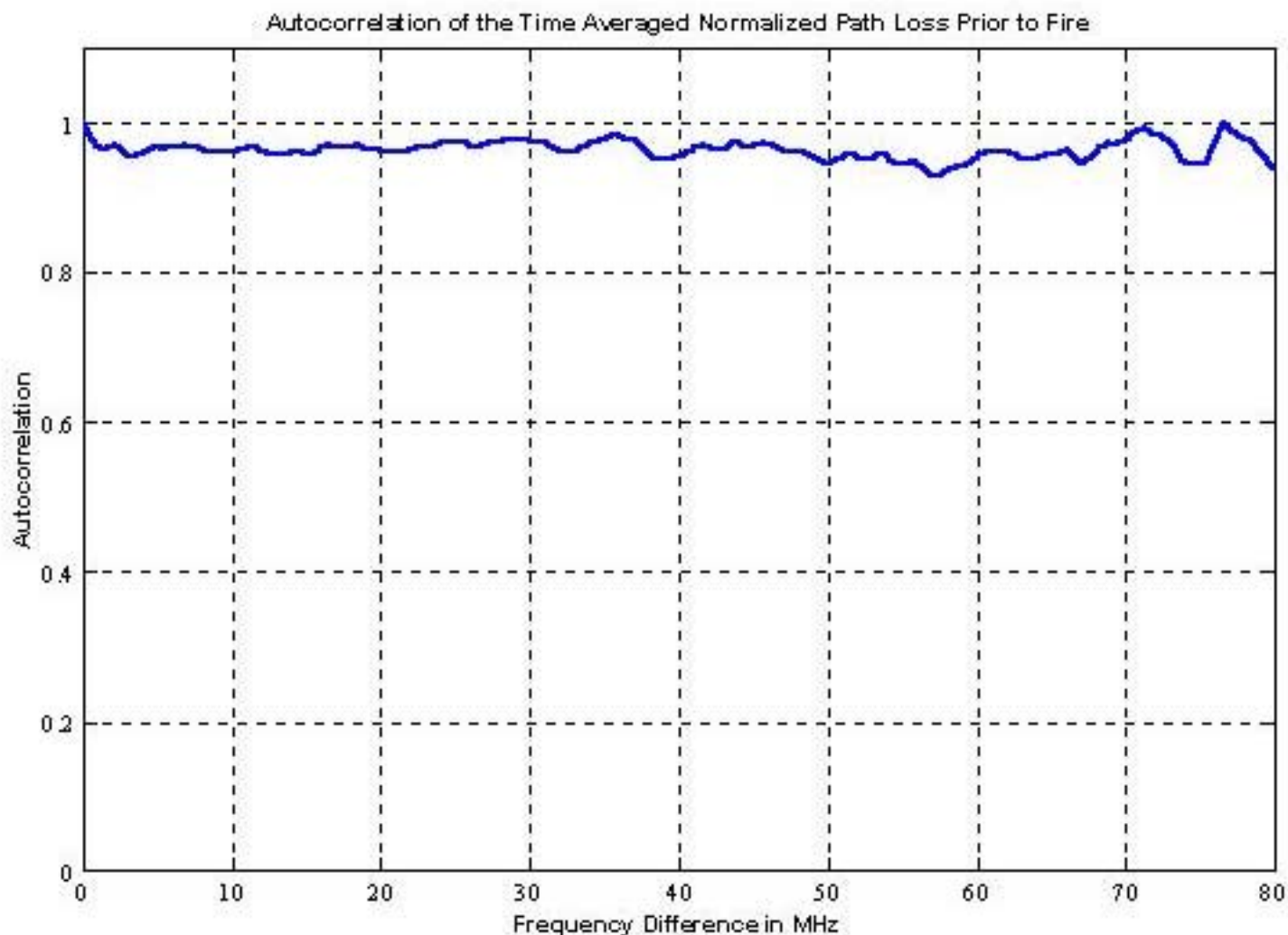


Average (all phases) Attenuation CDF for H-Pol



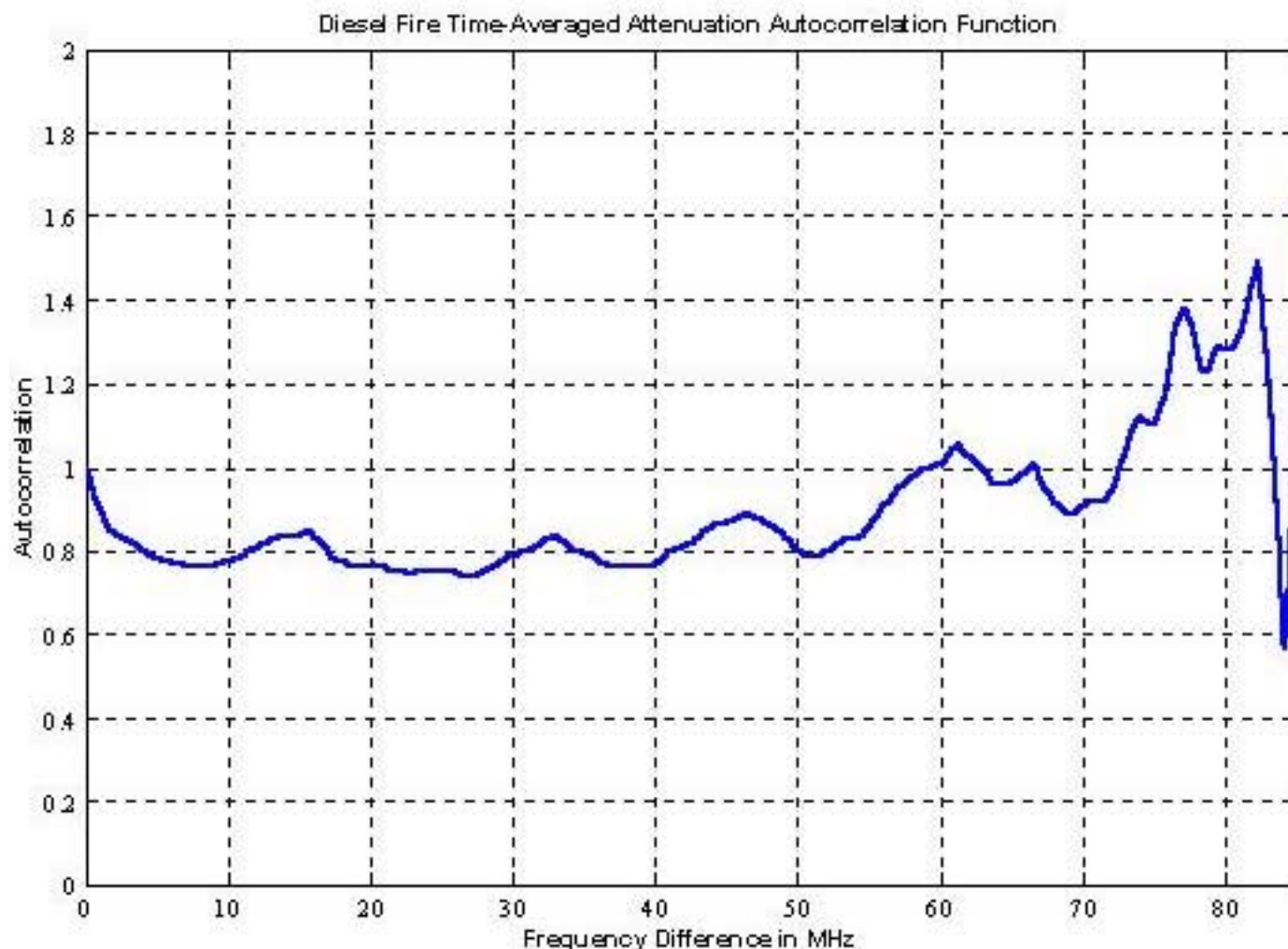


Normalized Autocorrelation Function for Patch Antennas Prior to Fire, H-Pol



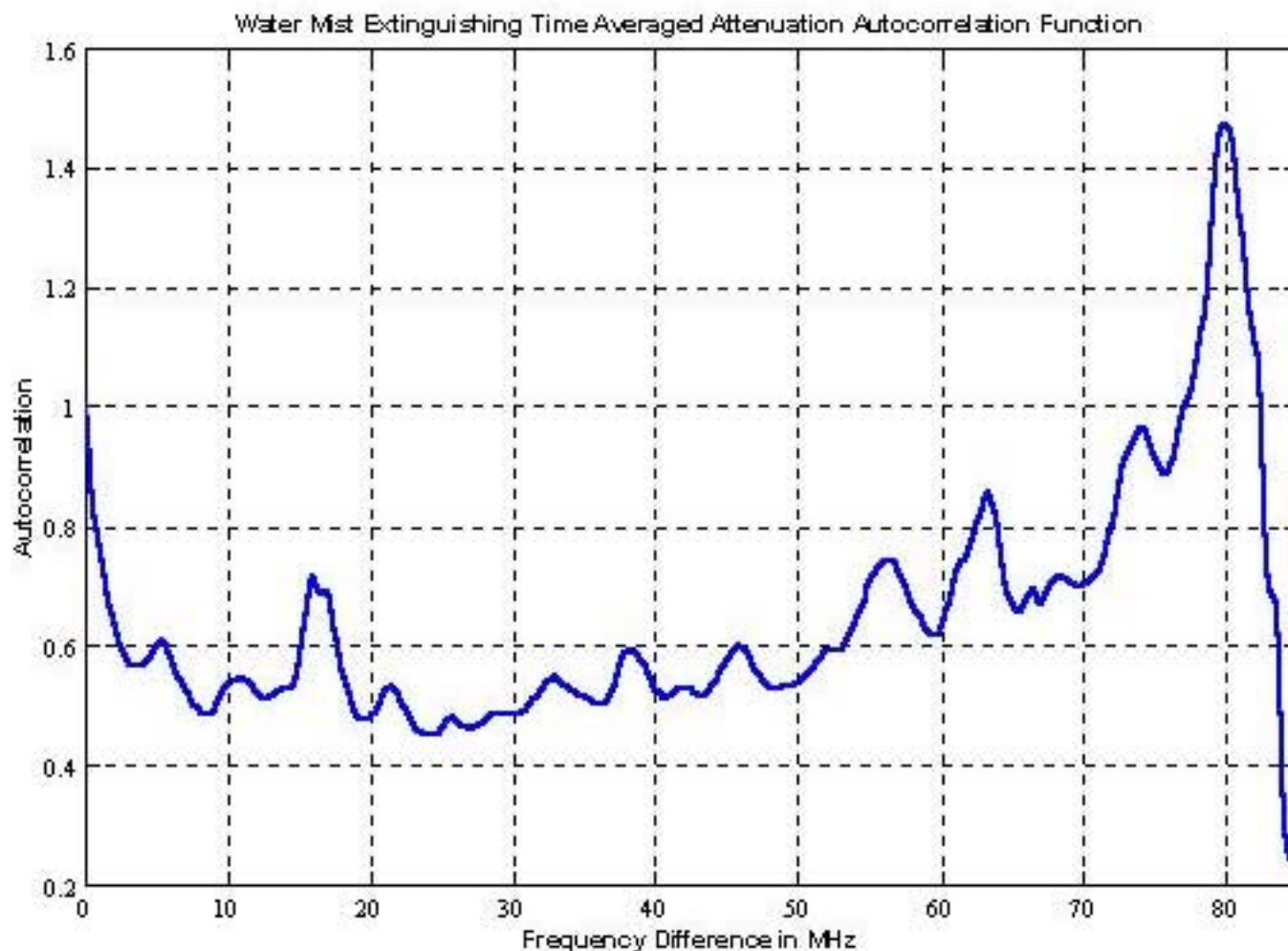


Diesel Fire Normalized Autocorrelation Function for Patch Antennas, H-Pol



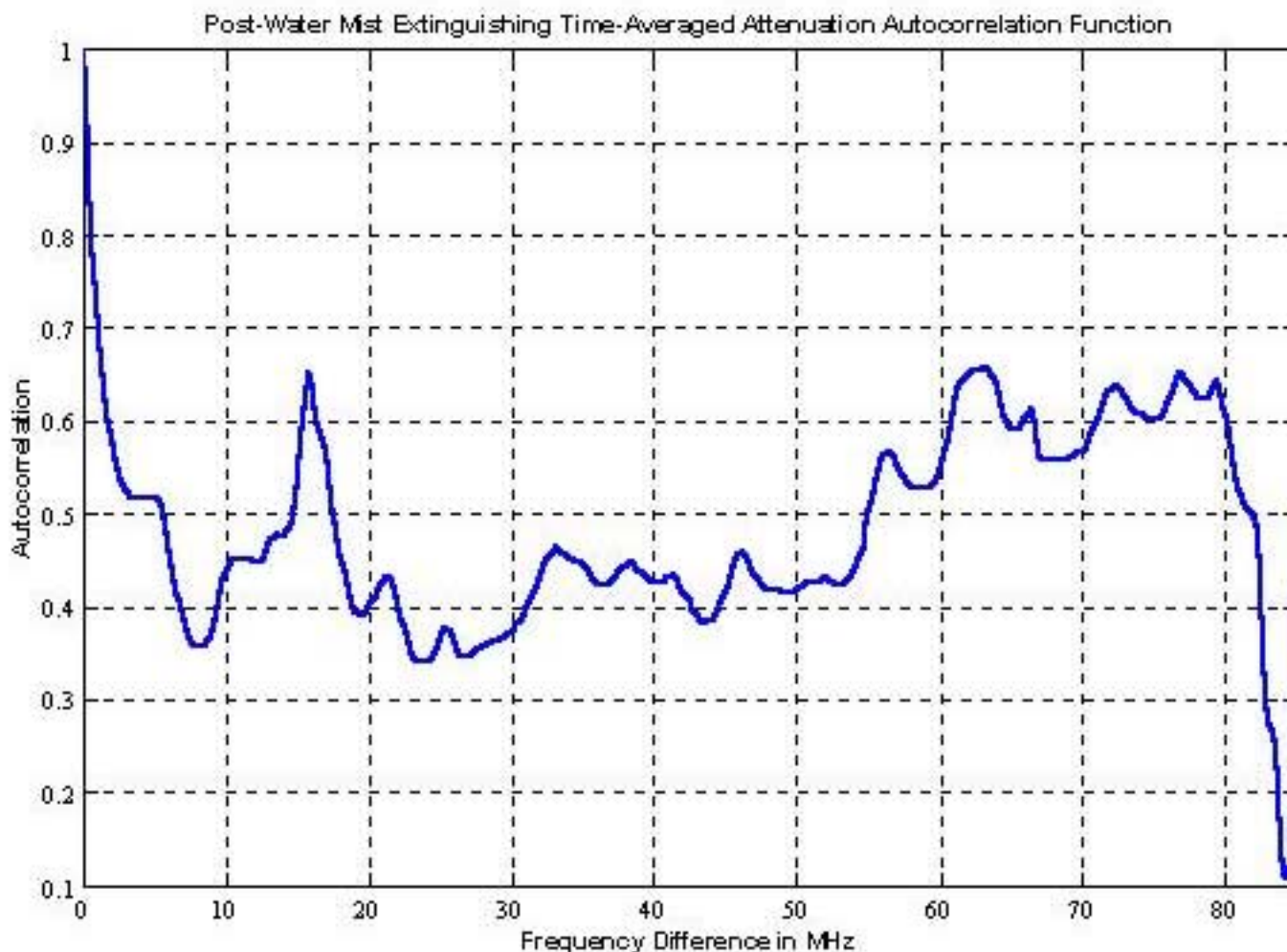


Water Mist Extinguishing Normalized Autocorrelation Function for Patch Antennas, H-Pol





Post-Water Mist Extinguishing Normalized Autocorrelation Function for Patch Antennas, H-Pol



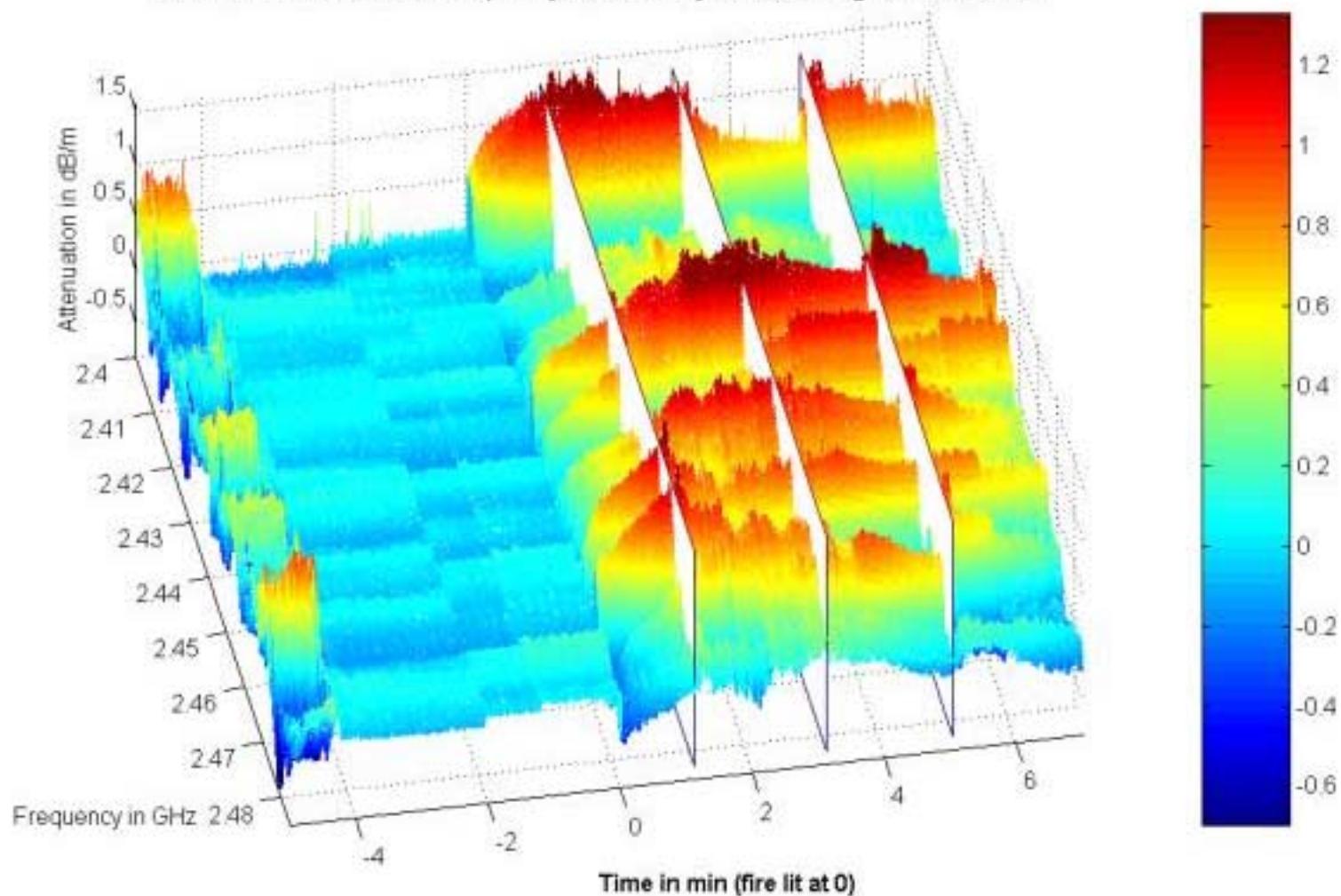


Heptane Fire Results for Vertically Polarized Directional (High Gain) Antennas



Attenuation for Directional Antennas, V-Pol

Attenuation vs Time and Frequency for Vertically Polarized High Gain Antennas

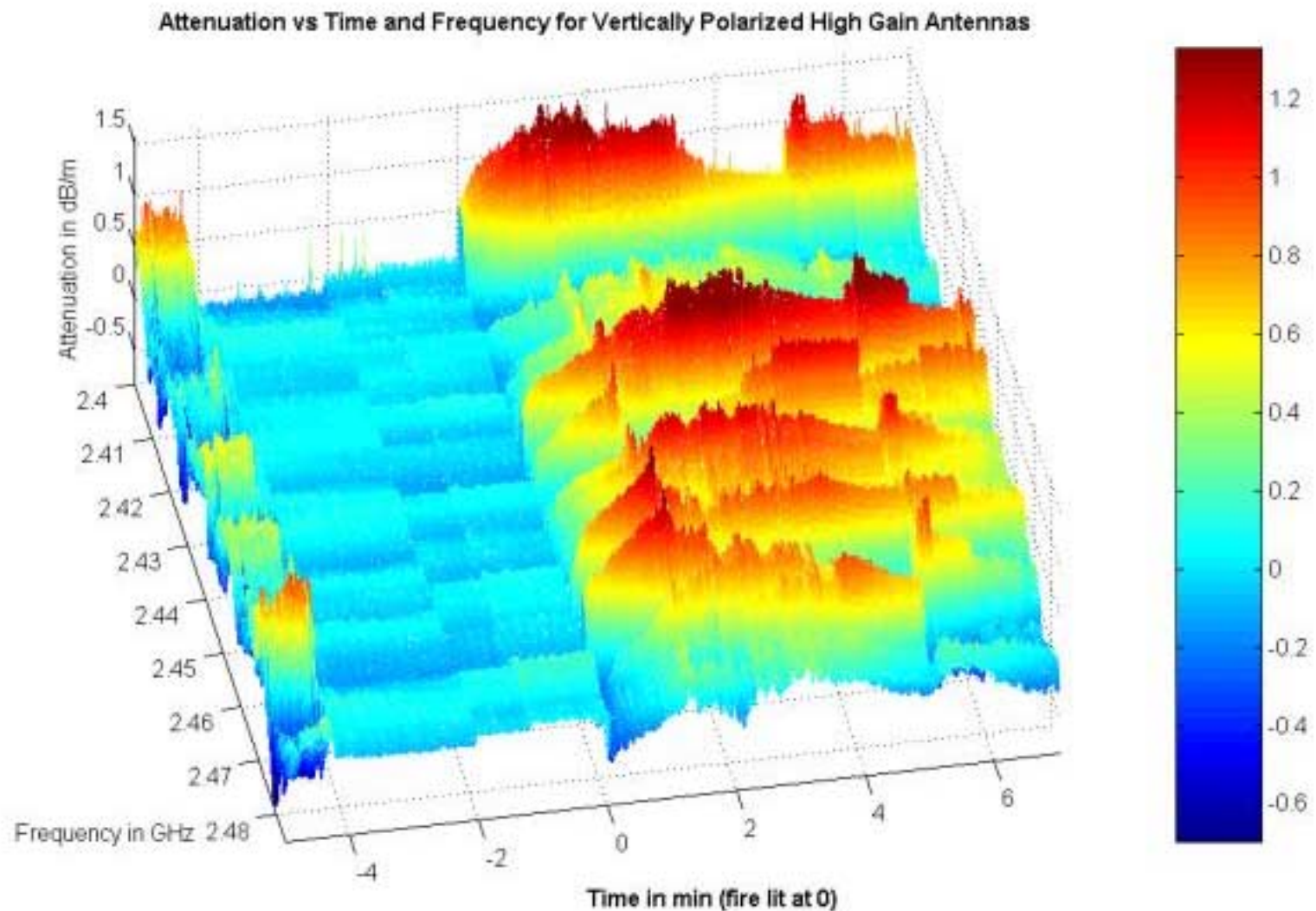




Measurements at ex-USS Shadwell

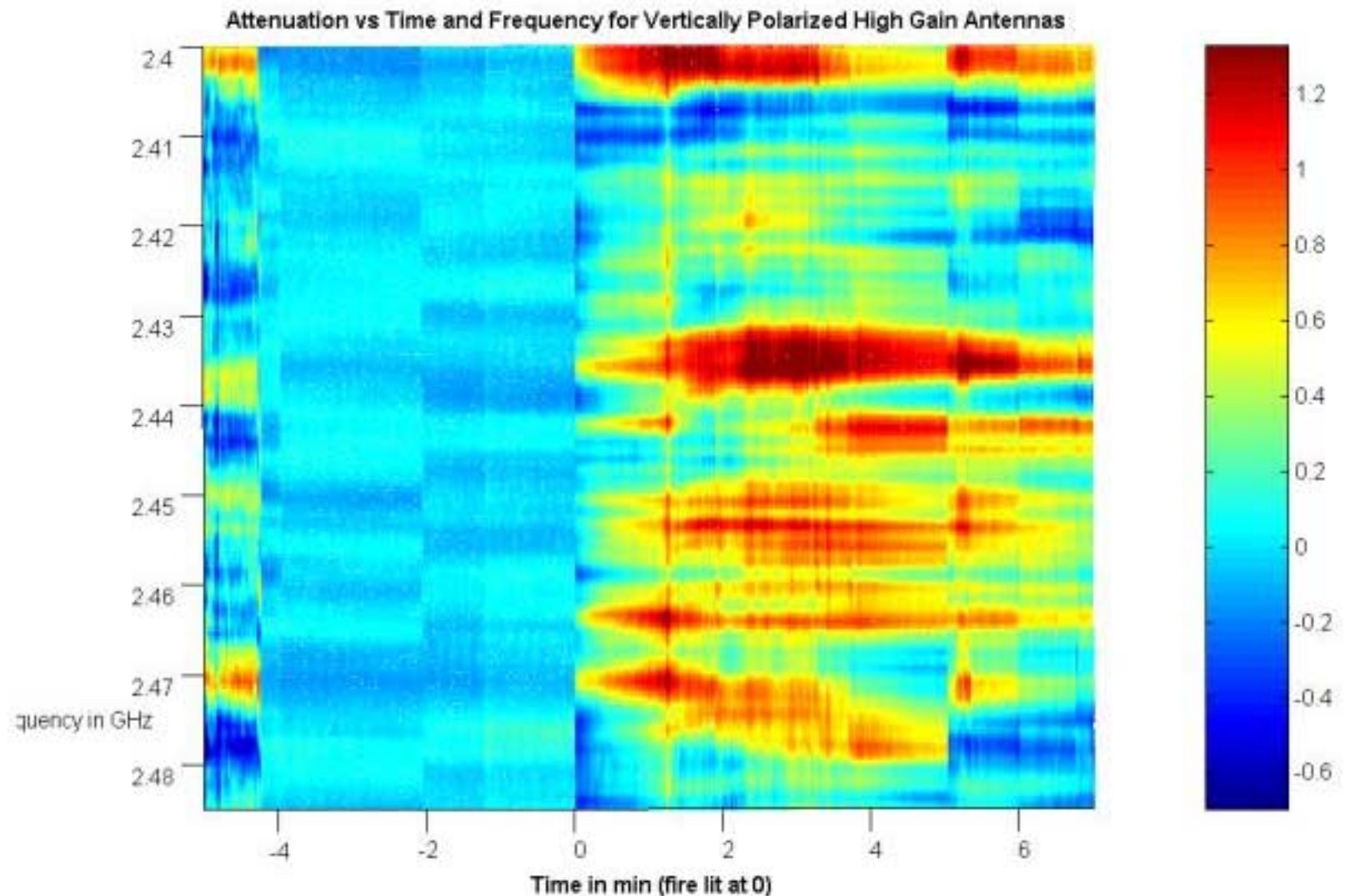


Attenuation for Directional Antennas, V-Pol



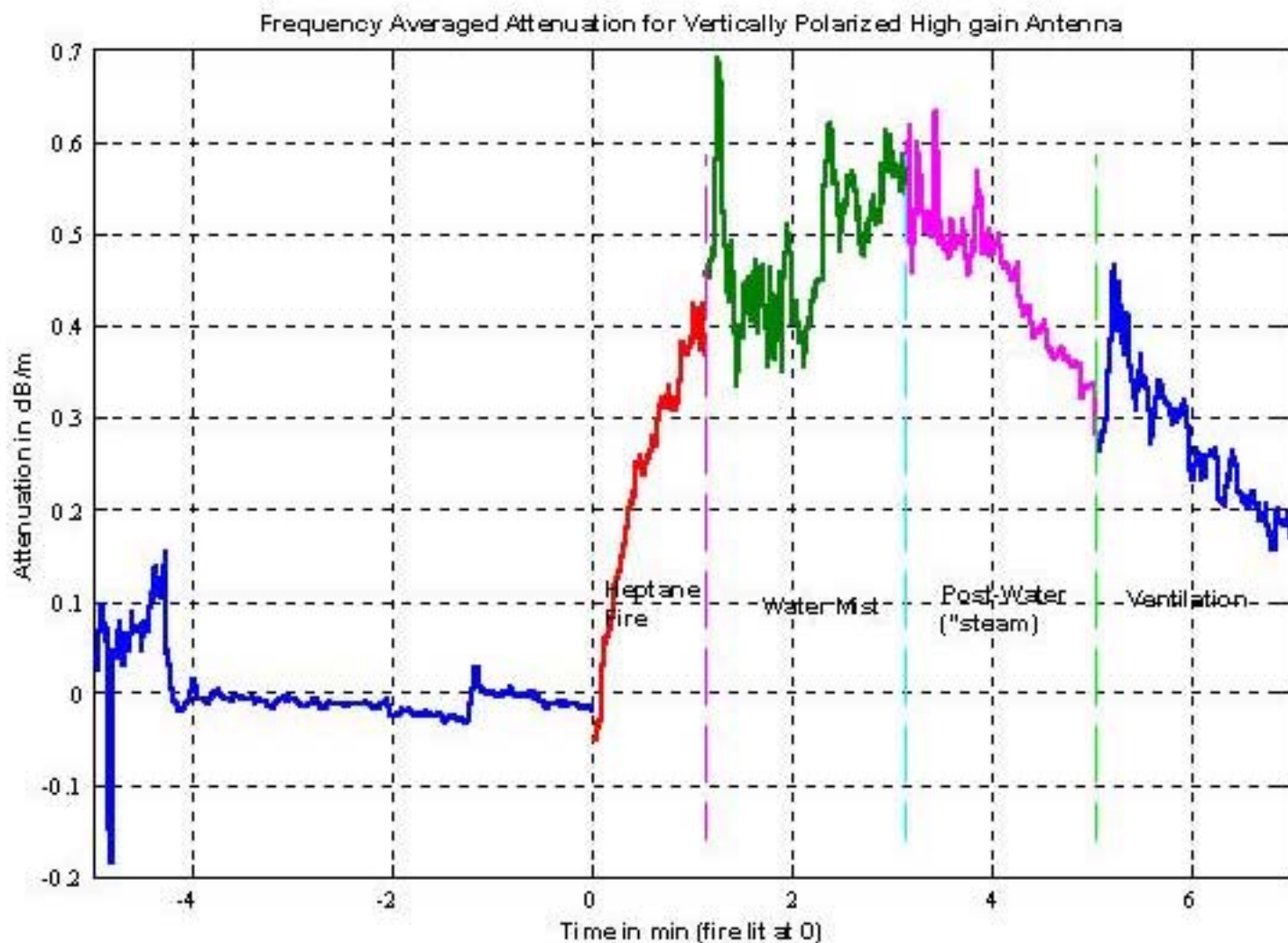


Attenuation for Directional Antennas, V-Pol



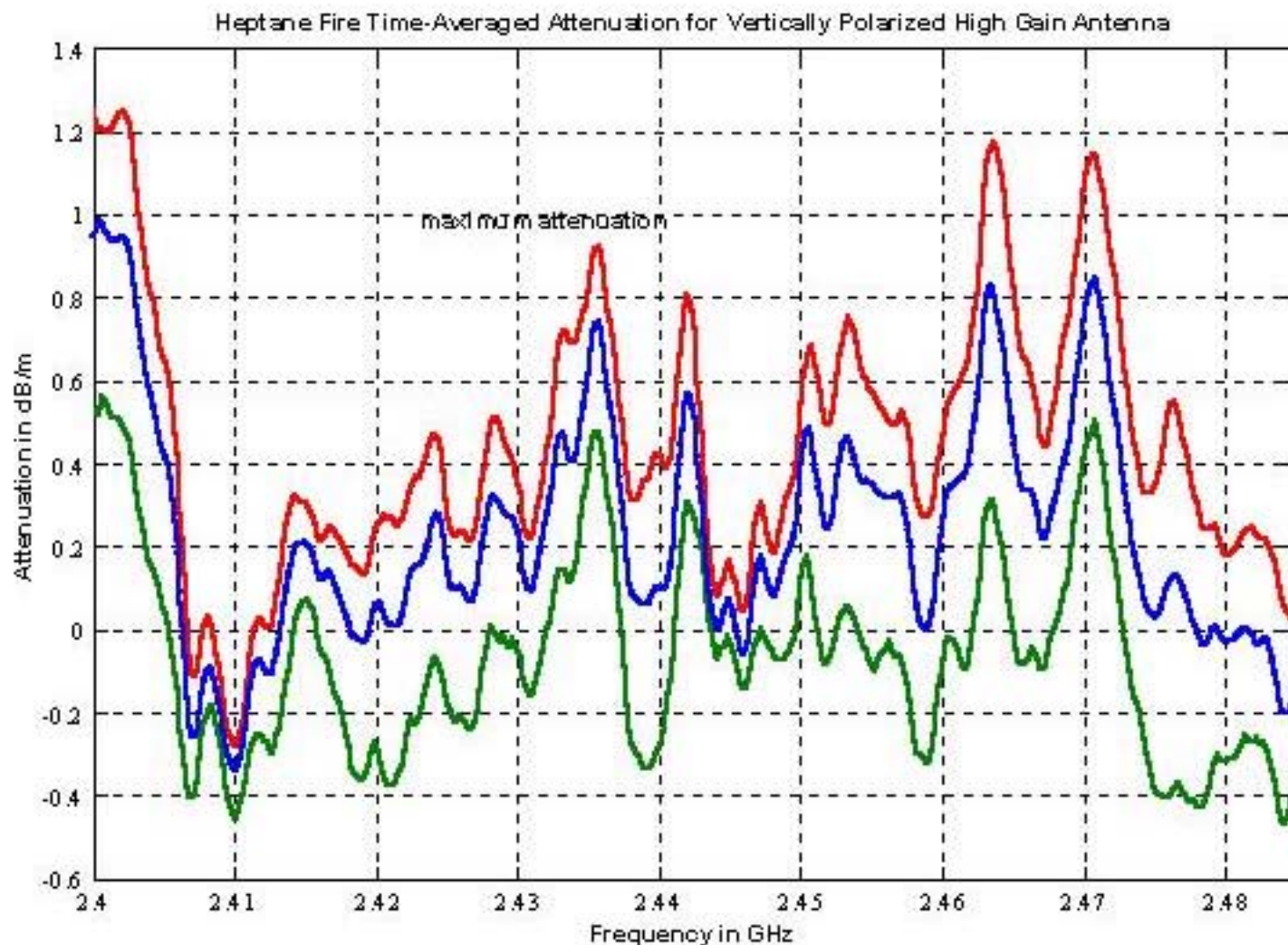


Frequency-Averaged Attenuation for Directional Antennas, V-Pol



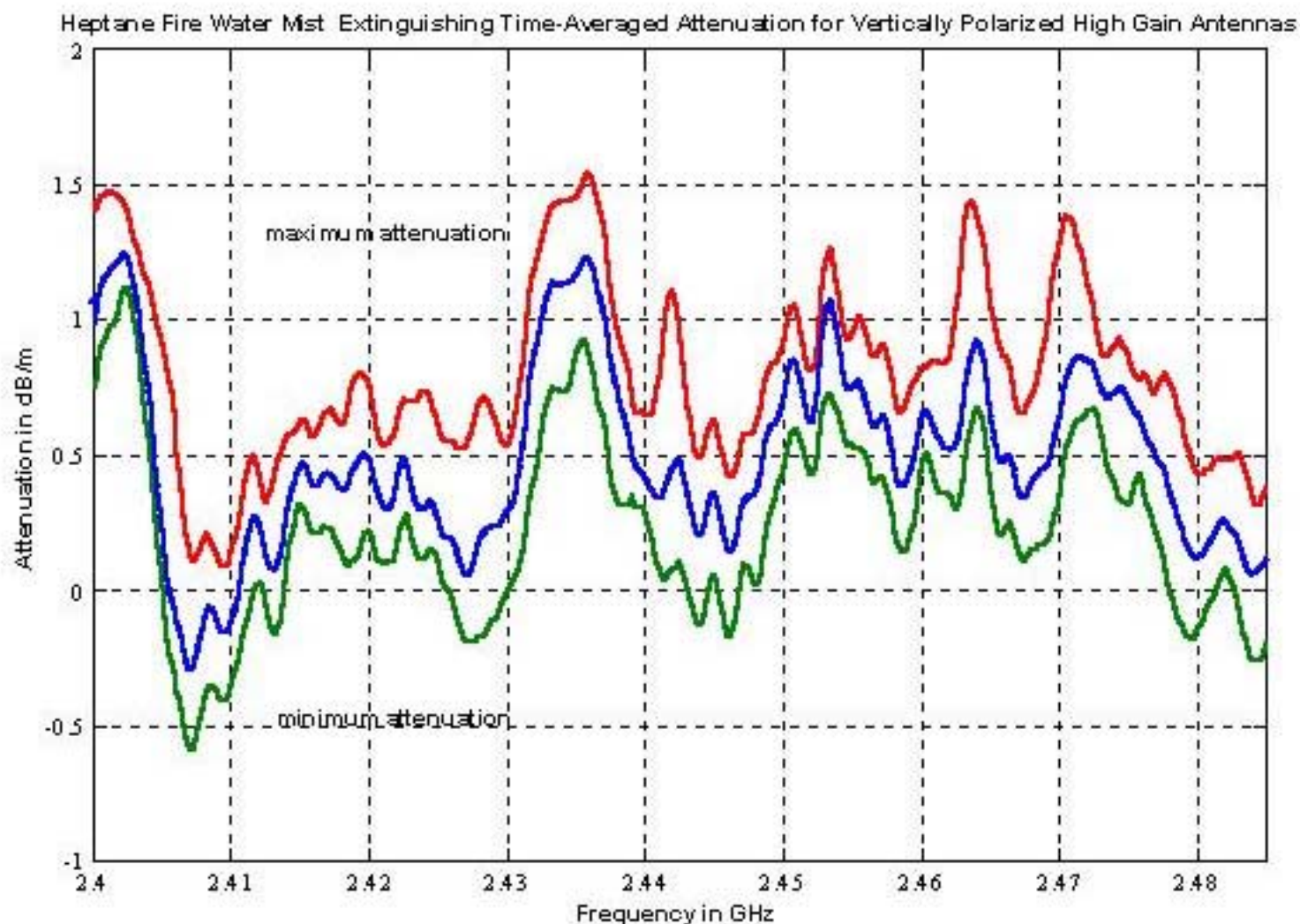


Heptane Fire Attenuation for Directional Antennas, V-Pol





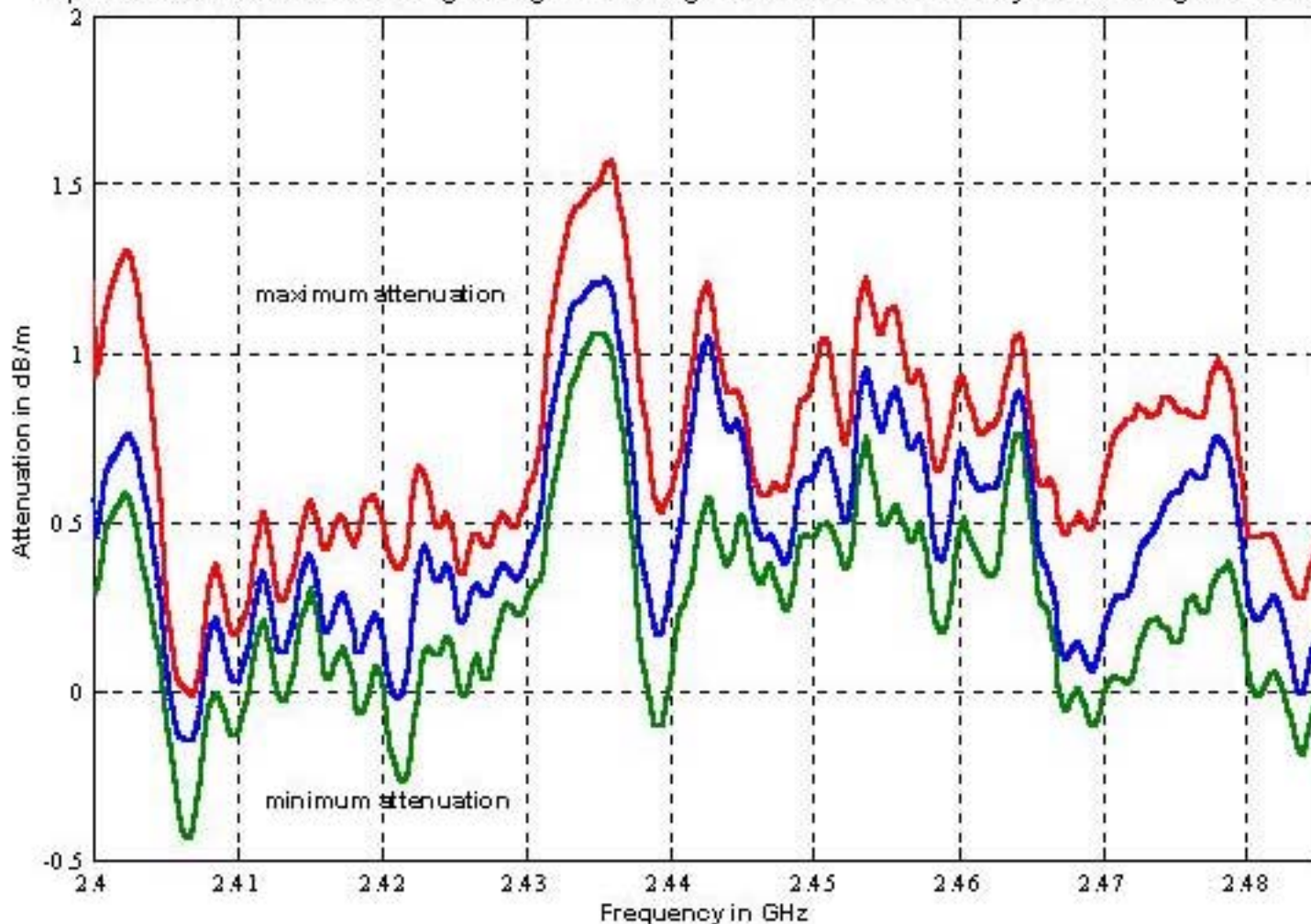
Water Mist Extinguishing Attenuation for Directional Antennas, V-Pol





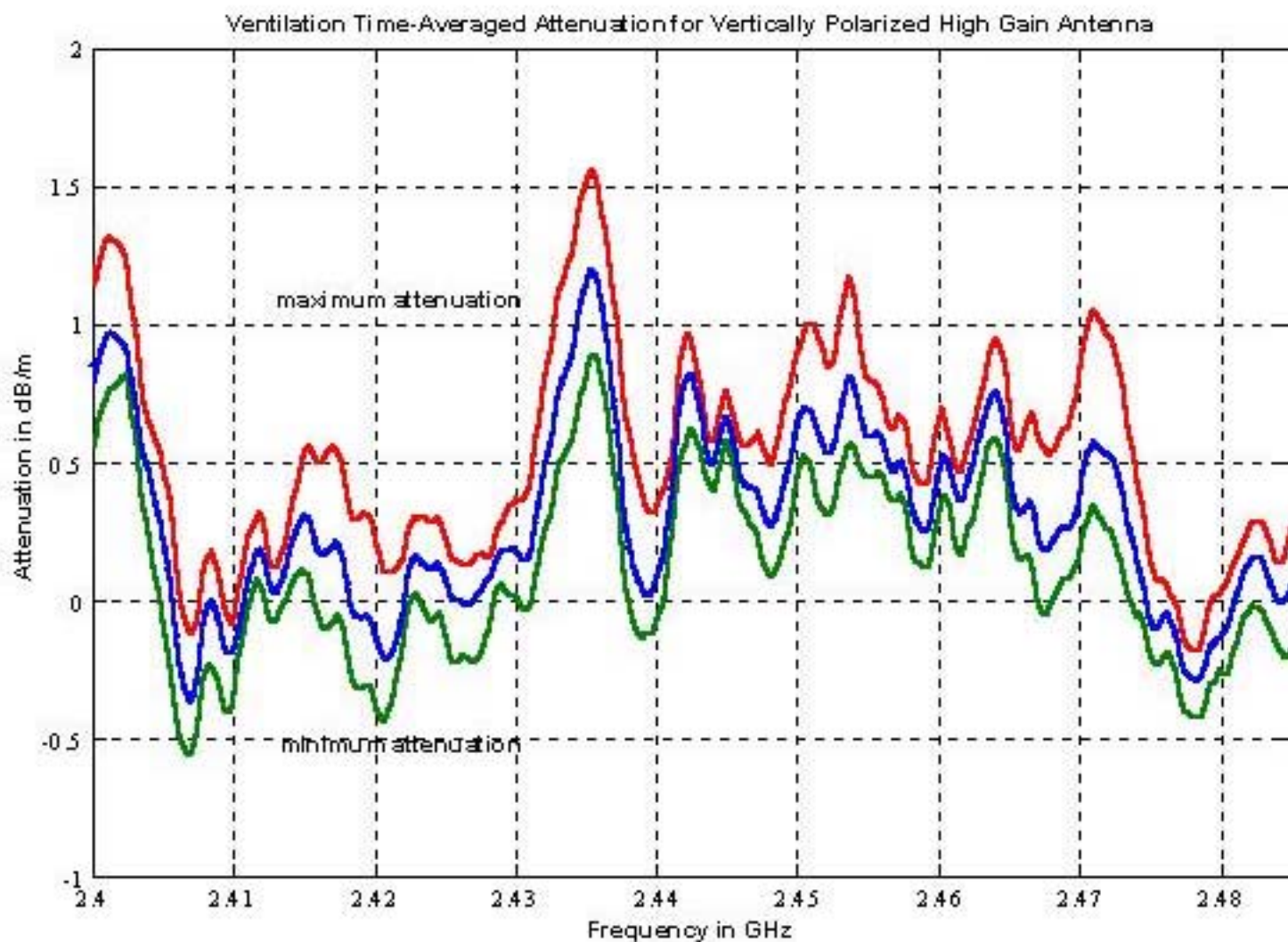
Post-Water Mist Extinguishing Attenuation for Directional Antennas, V-Pol

Heptane Fire Post-Water Mist Extinguishing Time-Averaged Attenuation for Vertically Polarized High Gain Antenna





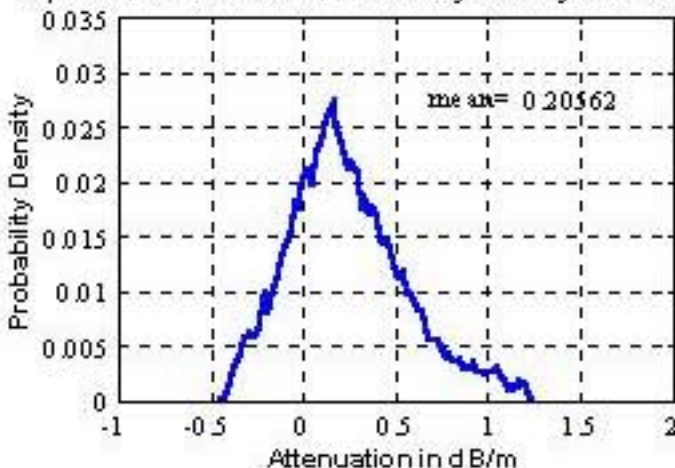
Ventilation Phase Attenuation for Directional Antennas, V-Pol



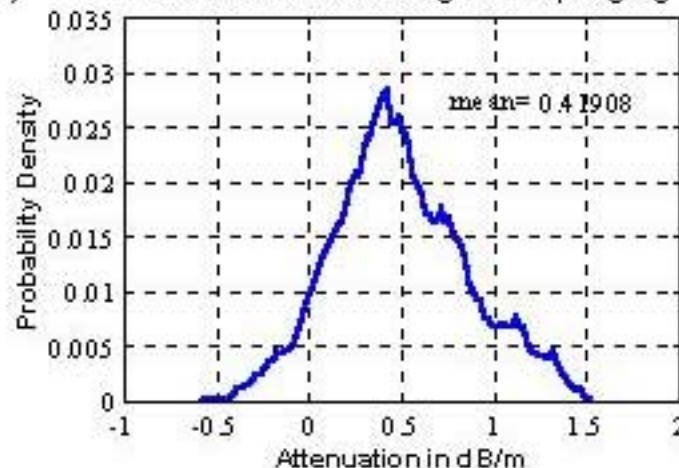


Attenuation Probability Density Functions for Directional Antennas, V-Pol

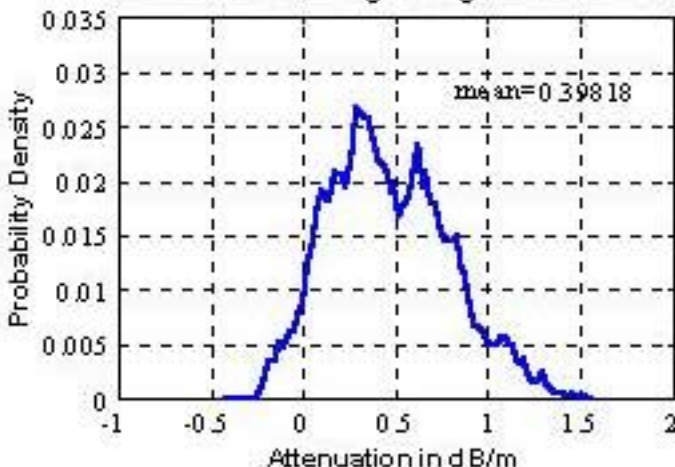
Heptane Fire Attenuation Probability Density Function (PDF)



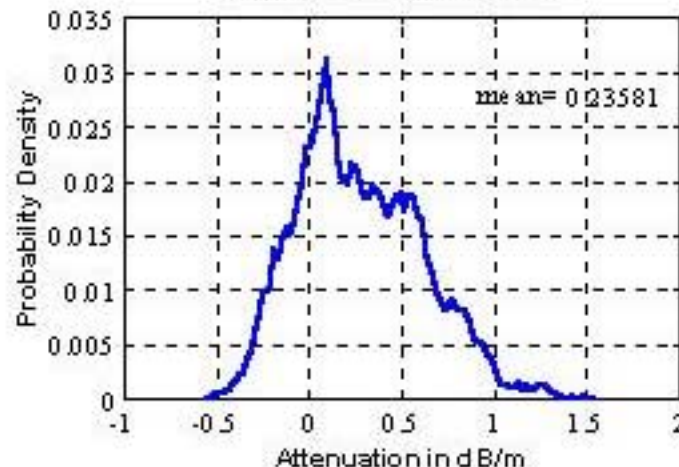
PDF of Attenuation during Water Springling



Post-Water Mist Extinguishing Attenuation PDF

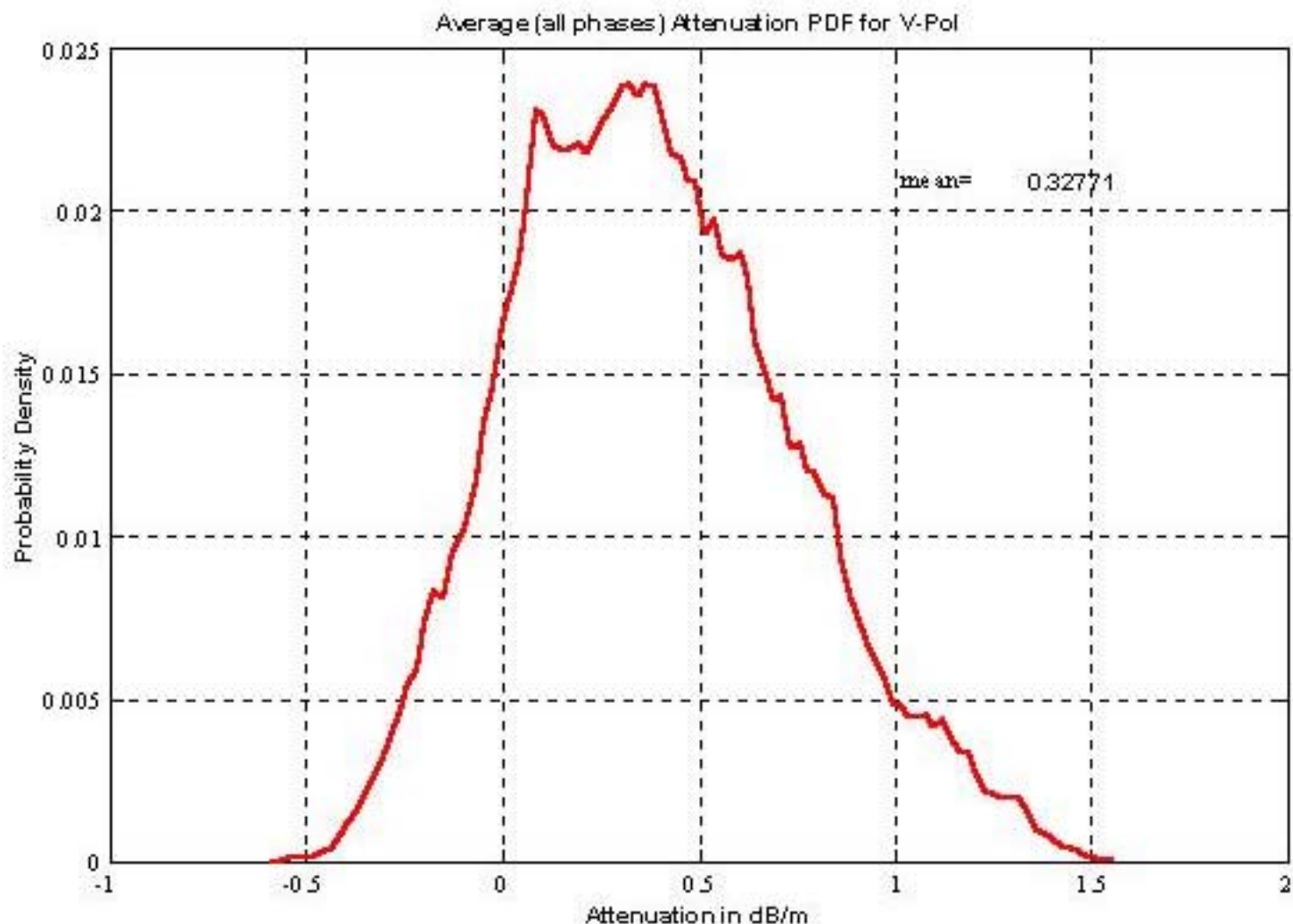


Ventilation Attenuation PDF





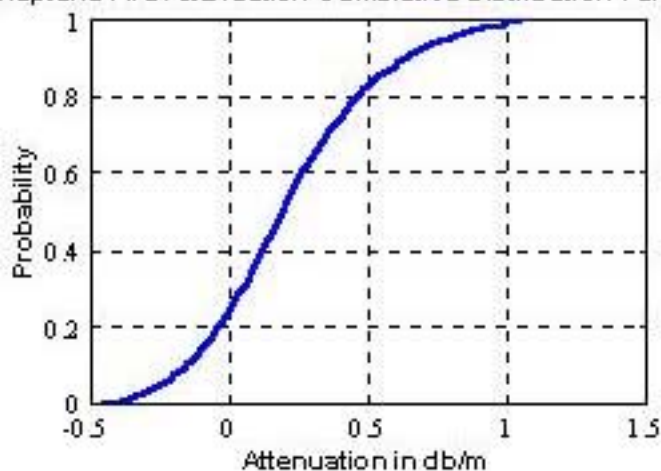
Average Attenuation Probability Density Function for Directional Antennas, V-Pol



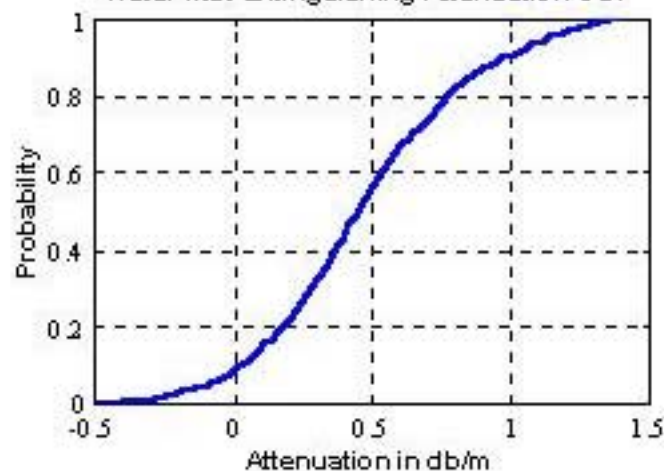


Attenuation Cumulative Distribution Functions for Directional Antennas, V-Pol

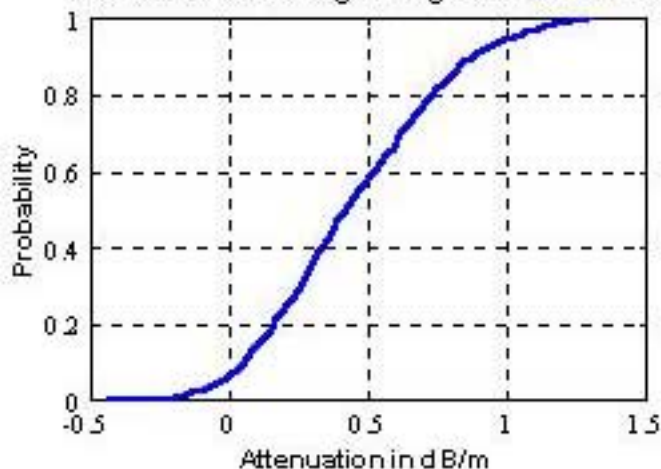
Heptane Fire Attenuation Cumulative Distribution Function



Water Mist Extinguishing Attenuation CDF



Post-Water Mist Extinguishing Attenuation CDF



Ventilation Attenuation CDF

